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DRL T-350
Line Item 4
MSC 05219
MB-R-71/105

CR 115483

FINAL REPORT

A SHUTTLE AND SPACE STATION MANIPULATOR SYSTEM FOR ASSEMBLY, DOCKING, MAINTENANCE, CARGO HANDLING AND SPACECRAFT RETRIEVAL

(PRELIMINARY DESIGN)

Volume IV - Simulation Studies

7 January 1972

Prepared For:

National Aeronautical and Space Administration
Manned Spacecraft Center
Houston, Texas 77058

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Bollinger Canyon Road
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Details of illustrations in this document may be better studied on microfiche

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FOREWORD

This final report presents the results of a four-month preliminary design study performed by MBAssociates under contract to NASA Manned Spacecraft Center (MSC). Mr. Richard Davidson was the MSC Program Technical Manager, Mr. Donald F. Adamski, the MBA Program Manager and Mr. James Cooper, the MBA Project Engineer. MBAssociates was the overall system designer and integrator. Perceptronics, Inc. and Control Data Corporation, under subcontract to MBA, were responsible for man-machine interface, supervisory computer control system and head-aimed foveal TV system support, respectively. Hamilton Standard Division, United Aircraft and Garrett Corporation, AiResearch Manufacturing Division contributed generously of their time to provide technical support and background information on environmental control, life support and power supply systems. In addition, MBA consultants, Messrs. Kentner Wilson, Carl Flatau, Robert Rumble and Dr. William Gerberich contributed significantly to this effort.

The study was divided into two phases. Phase 1 consisted of concepts development and selection. Phase 2 consisted of further analyses and refinement of the design selected in Phase 1 and of simulation studies in certain critical control and viewing system areas.

The Final Report consists of four volumes as follows:

Volume I - Management Summary

Volume II - Concept Development and Selection

Volume III - Concept Analysis
(Part I - Technical)
(Part II - Estimated Development Program)

Volume IV - Simulation Studies

A detailed presentation to NASA MSC on concepts development and selection was given at Houston, Texas on 30 August 1971. Presentation Aids for that briefing are given in MBA Document MB-R-71/85. Volume II of this Final Report does not present all of the information given at the briefing, but instead summarizes all of the important elements of that briefing. Similarly, a final report summary presentation to NASA MSC was given by MBA at Houston, Texas on 3 December 1971. Presentation Aids for that briefing are given in MBA Document MB-R-71/107. Volume III contains all of the information presented at the final report briefing, including a description of the final preliminary design and the design analyses and tradeoff studies leading to finalization of the design.

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ABSTRACT

A preliminary design has been established for a general purpose manipulator system suitable for docking, cargo handling, assembly and maintenance operations in support of space shuttle and space station missions. The manipulator can be used interchangeably on the shuttle and station and can be transferred back and forth between them. Control of the manipulator is accomplished by hard wiring from internal control stations in the shuttle or station. A variety of shuttle and station manipulator operations have been considered including servicing the Large Space Telescope; however emphasis has been placed on unloading modules from the shuttle and assembling the space station. Simulation studies on foveal stereoscopic viewing and manipulator supervisory computer control have been accomplished to investigate the feasibility of their use in the manipulator system.

The basic manipulator system consists of a single 18.3m (60') long, 7 degree of freedom (DOF), electrically actuated main boom with an auxiliary 3 DOF electrically actuated, extendible 18.3m (60') maximum length, lighting and viewing boom. A 3 DOF orientor assembly is located at the tip of the viewing boom to provide camera pan, tilt and roll. Primary viewing is accomplished with a black and white and color stereoscopic, foveal, zoomable TV system. Direct viewing is used as a backup where possible. TV cameras and lights are mounted on the main boom, the auxiliary boom and on the space station and shuttle. The main boom can exert a tip force of 111 Newtons (25 lbs) at which a tip deflection of 0.142m (5.6") occurs for the boom fully extended (straight out). The main boom actuators incorporate slip clutches to prevent actuator/boom overloads. The main boom is symmetrical about the elbow and consists of two 8.15m (27') long arms each having identical 3 DOF, 1m (3.29') long wrist assemblies. The boom can be operated from either end and is capable of walking end-over-end from one root point to another. Root points are located strategically about the station and shuttle so that the desired working envelopes can be accessed for cargo handling assembly, repair and maintenance.

The end connectors on the main boom plug directly into the root points so that no special end effectors are required for station assembly and cargo handling operations. The basic manipulator system weighs approximately 421 kgms (930 lbs). Additional boom and general purpose and/or special purpose end effectors can be added as required for other operations. A preliminary program estimate has been made for development and flight qualification of the manipulator system, including a dexterous general purpose end effector and including ground simulations, and operator training up to, but not including, orbital flights.

The results of this preliminary design study are presented in four volumes as follows:

- Volume I - Management Summary
- Volume II - Concept Development and Selection
- Volume III - Concept Analysis
  - (Part I - Technical)
  - (Part II - Estimated Development Program).
- Volume IV - Simulation Studies

Volume II describes the various concepts considered and the rationale for the selected design. Volume III describes the selected preliminary design and the supporting design and tradeoff analyses.

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1.0 DEFINITIONS

Aberration - Any errors that result in the imperfection of an image.

A/D - Analog to digital conversion subsystem

AEC - Atomic Energy Commission

D/A - Digital to analog conversion subsystem

Fovea - The central part of the eye retina presenting maximum acuity.

Foveal - The central part of the field of view.

MBA - MBAssociates

MSC - NASA Manned Spacecraft Center

NASA - National Aeronautics & Space Administration

NAT - Naval Anthropomorphic Teleoperator

SNSO - NASA/AEC Space Nuclear Systems Office

Split-Field Television - Use of adjacent images in one camera and one monitor of a television system.

Stereo-Foveal - The central part of the field of view is stereoscopic.

Stereo-Foveal-Peripheral - A system with two combined fields of view, of which the central or foveal one is stereoscopic and the outer or peripheral one is monocular.

TFC - Trajectory Following Control

Visual Acuity - The ability of an observer to perceive fine detail.

$F(t)$ - Input time function which describes the trajectories of the mini-controller; a vector whose components define the motions of each of the joints.

$\tilde{F}(t)$ - The smoothed time expanded trajectory function

β - Time expansion factor

δ_i - Rate of change of $F(t)$

δ_o - Lowest value of δ_i which is considered significant to indicate a motion.

$\tilde{F}(\beta t)$ - Expanded time trajectory

m - mass

a - scale factor

k - spring constant

x - displacement

S - Laplace variable

f - frequency

T - period

F - force

2.0 SUMMARY

Volume I, Volume II, and Volume III, of this report discuss the need for and/or desirability of including in the multipurpose Shuttle and Space Station manipulator system the following concepts:

- A stereo-foveal-peripheral TV system
- A computer assisted model control system termed the Trajectory Following Control (TFC) System
- Active damping of the slave boom

This volume and its ancillary motion picture film establishes the feasibility of these concepts through simple, somewhat crude but conclusive laboratory simulations. These simulations were carried out under a modification to the basic study contract. In all cases the prime objective was only to prove feasibility of the concept and not to absolutely test the design evolved for the multipurpose Shuttle and Space Station manipulator system. Accordingly, the specific simulation setups described are based on maximum use of available off-the-shelf hardware elements (MBA, NASA/MSC and Navy/NASA/AEC) for an absolute minimum cost effort. The systems described were not intended to be optimum embodiments and should not be considered as such.

A single copy of an 11-minute long 16mm silent color motion picture film, which allows the reader to physically observe the Trajectory Following Control system (TFC) in action, accompanies this volume. Similar documentation of the stereo-foveal-peripheral TV system was not feasible. Stereo slides taken through the laboratory apparatus are available, but a stereo viewer is required to use them. The slides, however, considerably degrade the quality of the actual TV display. Conversion of the slides to black and white photographs degrade the display further and half-tone printing in a report such as this degrades them still further. As a consequence, they are presented only to provide an indication of their nature. Interested readers are urged to contact Donald F. Adamski at MBA to arrange a visit to the plant to observe first-hand this state-of-the-art system.

The following section describes each of the three simulations in the order presented above and under the following breakdown: Introduction, Objectives, Description and Results. Appendix A presents a descriptive narrative for the TFC film which is divided into five scenes.

3.0 STEREO-FOVEAL TELEVISION SYSTEM WITH SYMMETRIC STEREOSCOPIC SPLIT-IMAGE REGISTRATION AND 90 DEGREE COUNTER-ROTATION

3.1 Introduction

Split-field stereoscopic and eye acuity matching (foveal-peripheral) television systems have been demonstrated before, but only as separate systems. The symmetric stereoscopic split-field image registration concept had also been formulated (J. Jones, NASA Ames) but not translated into practice. This simulation study proposed to assemble and evaluate a system that incorporates the above features, plus a unique system producing 90 degree field counter-rotation, to yield an improved remote viewing subsystem for use in teleoperator systems.

The specific system configuration used in the described simulation was based on the use of available off-the-shelf hardware elements (MBA, NASA/MSC and NASA/AEC/SNSO) for an absolute minimum cost effort. The system was not intended to be an optimum embodiment and should not be considered as such.

3.2 Objectives

- Prove feasibility and performance of the stereo-foveal-peripheral integration concept.
- Evaluate the monocular peripheral field combined with stereo-foveal field concept on the assumption that since the wide, low resolution field is peripheral and only dimly perceived, stereo is not necessary for it.
- Evaluate the split-field symmetry concept involving 90 degree counter-rotation of the two halves of the field for elimination of picture tube distortion and optimization of stereoscopic perception acuity.
- Evaluate display options like: virtual images at infinite or finite distance, effects of zooming, etc.
- Evaluate human factors.

3.3 Description

3.3.1 90 Degree Image Counter-Rotation

Cathode ray tubes possess aberrations (i.e., distortion, beam focusing, etc.) that are symmetric with regard to the tube center and that increase with distance from the center. With a simple split field stereoscopic video system it can be seen that the two images of the same detail of an object will have two different aberration levels because of their location on the screen. This will introduce extraneous disparities between the two stereoscopic images. These aberration-induced disparities are not produced by stereoscopic parallax and will degrade stereoscopic perception of the display by the observer (Figure 3.3.1-1).

Rotating the two stereo fields by 90 degrees in opposite directions will bring them to register symmetrically with regard to the image center both on the image tube and on the display tube (Figure 3.3.1-2). In this way, non-stereoscopic image disparities are eliminated. A further advantage is provided by the fact that the rotated image provides higher resolution in the horizontal direction, stereoscopic acuity being a function of horizontal resolution. Figure 3.3.1-3 shows the reflector arrangement that provides the 90 degree counter-rotation. The large number of reflectors used (5) is due to the fact that the two halves of the split field are adjacent at the image and cathode ray tubes.

3.3.2 Camera System

The laboratory prototype arrangement of the camera system is shown in Figure 3.3.2-1. Two cameras were used: peripheral and stereo. The fields of the two cameras were made to coincide by using a beam combiner (Figures 3.3.2-2 and 3.3.2-3). The stereo-foveal camera is a Sony AVC-3400 (MBA property) and the peripheral camera is a Sony CVC-2100A (NASA/AEC/SNSO property). A Stereotronics split field stereo adapter (NASA/MSC property) with remote convergence control was used for producing the two stereo fields. The adapter was modified to provide fine adjustment of convergence symmetry for the rotating

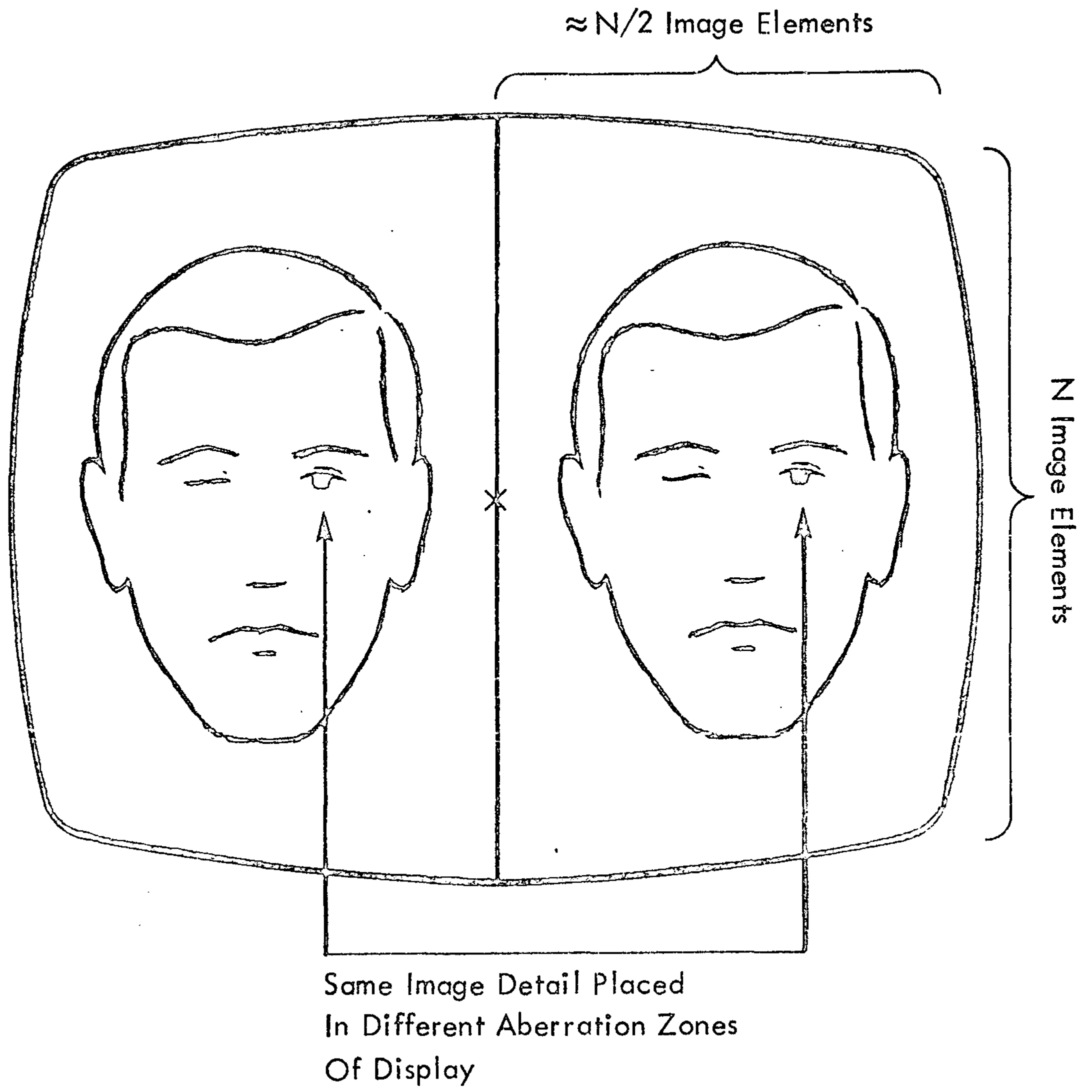

FIGURE 3.3.1-1.
CONVENTIONAL SPLIT FIELD STEREOSCOPIC VIDEO DISPLAY.
Non-Stereoscopic Image Disparities and Horizontal Resolution Lower Than Vertical Resolution.

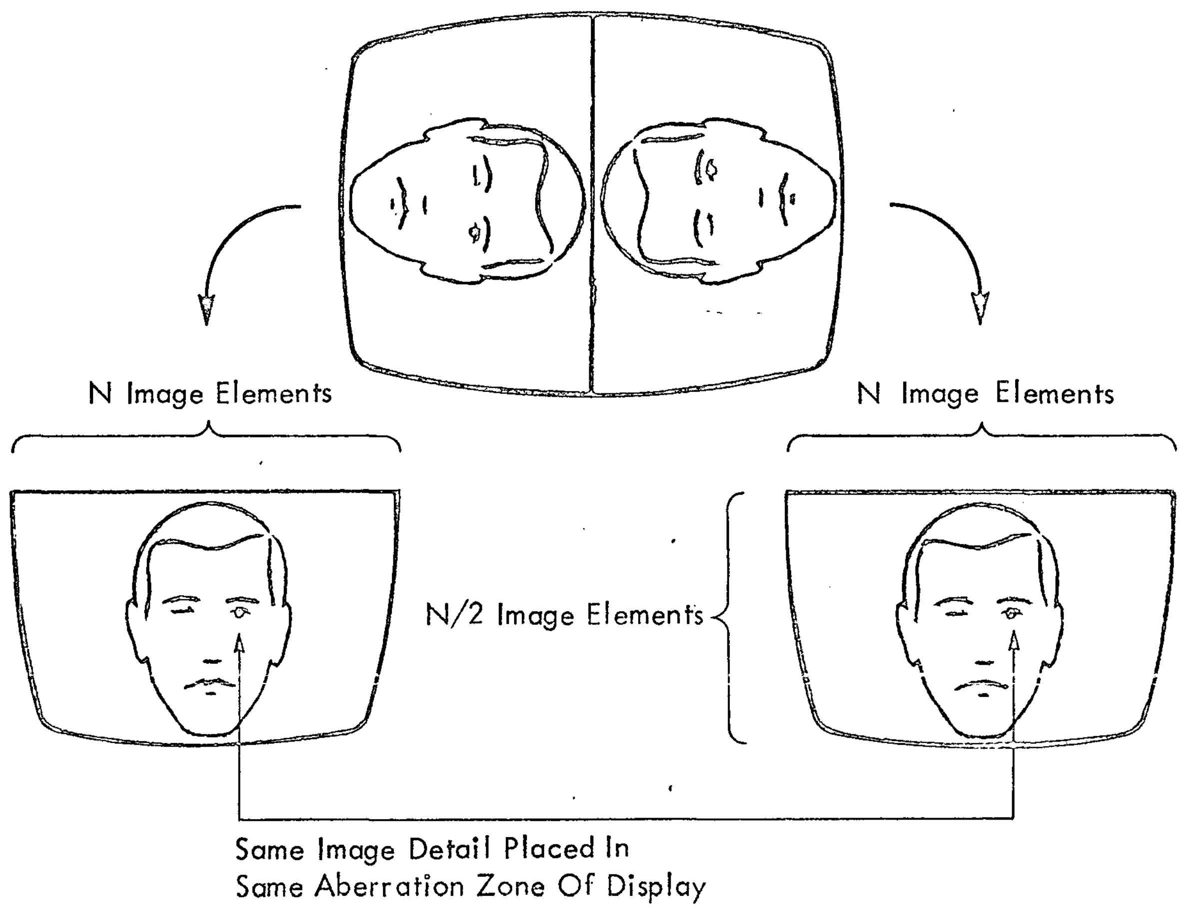

FIGURE 3.3.1-2.
SPLIT FIELD STEREOSCOPIC VIDEO DISPLAY WITH 90 DEGREE IMAGE COUNTERROTATION. Non-Stereoscopic Image Disparities. Horizontal Resolution Higher Than Vertical Resolution For Economy Of Bandwidth.

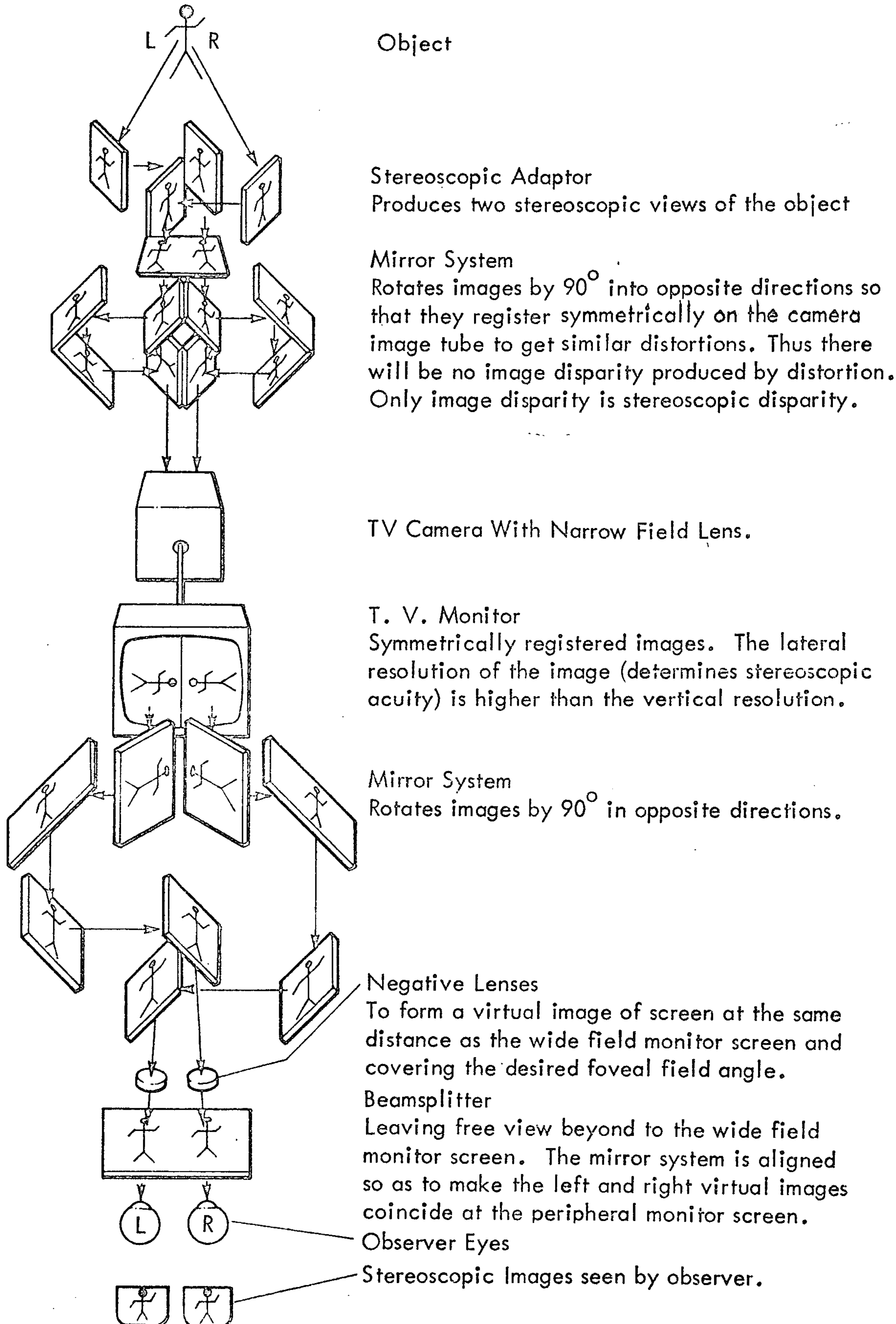

FIGURE 3.3.1-3.
MIRROR SYSTEMS AND IMAGE COUNTER ROTATION

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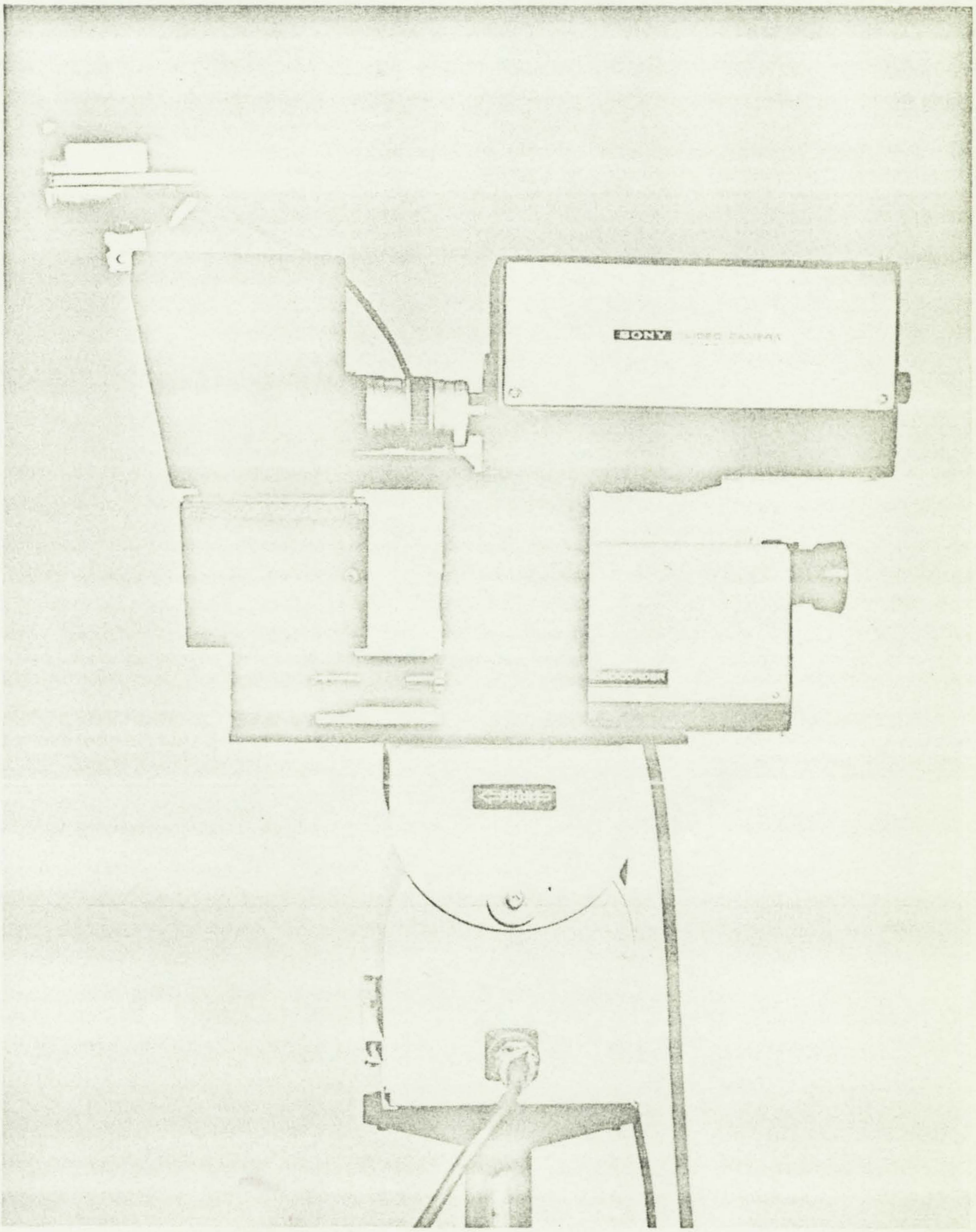

FIGURE 3.3.2-1.
CAMERA SYSTEM

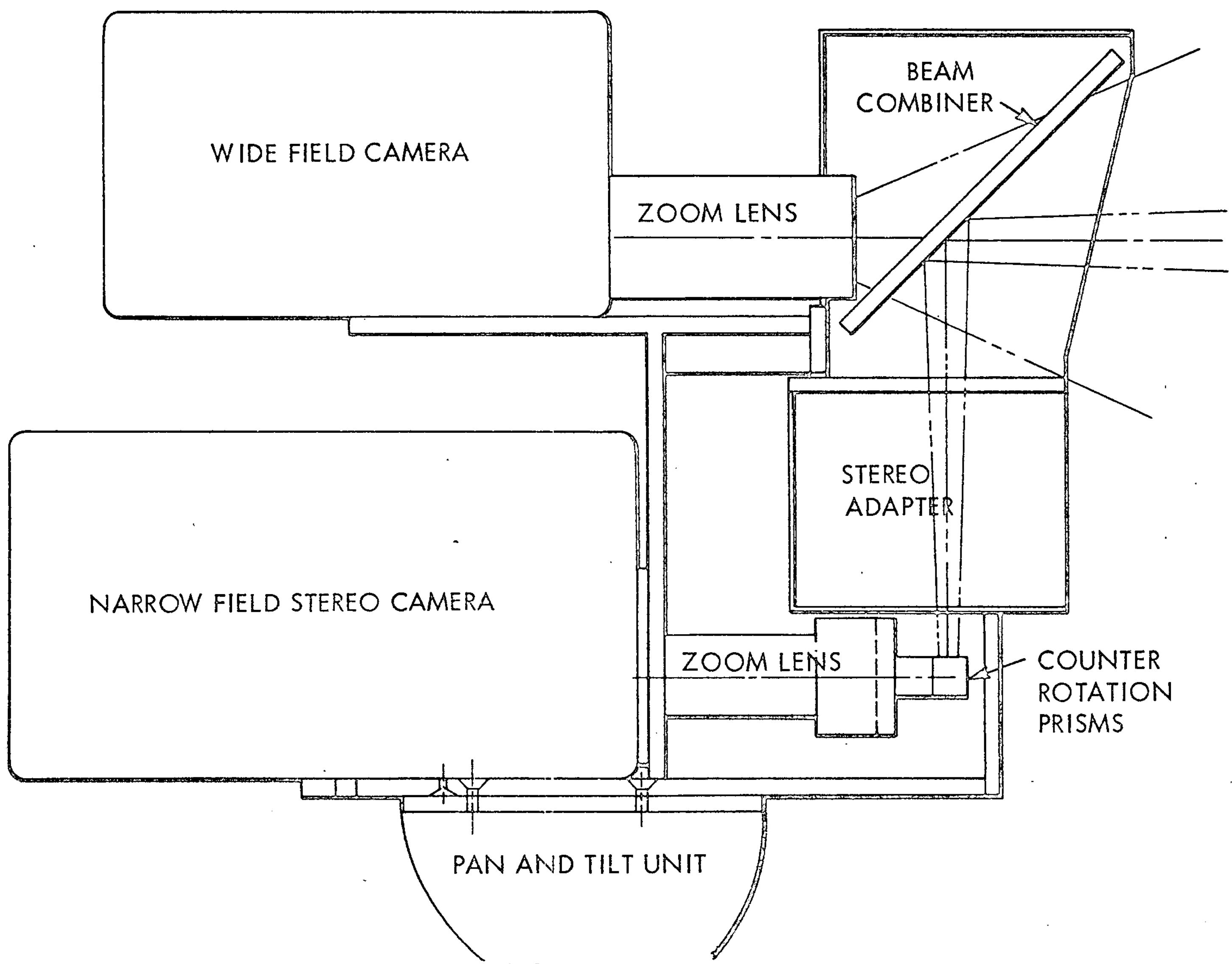

FIGURE 3.3.2-2.
STEREO-FOVEAL CAMERA SYSTEM

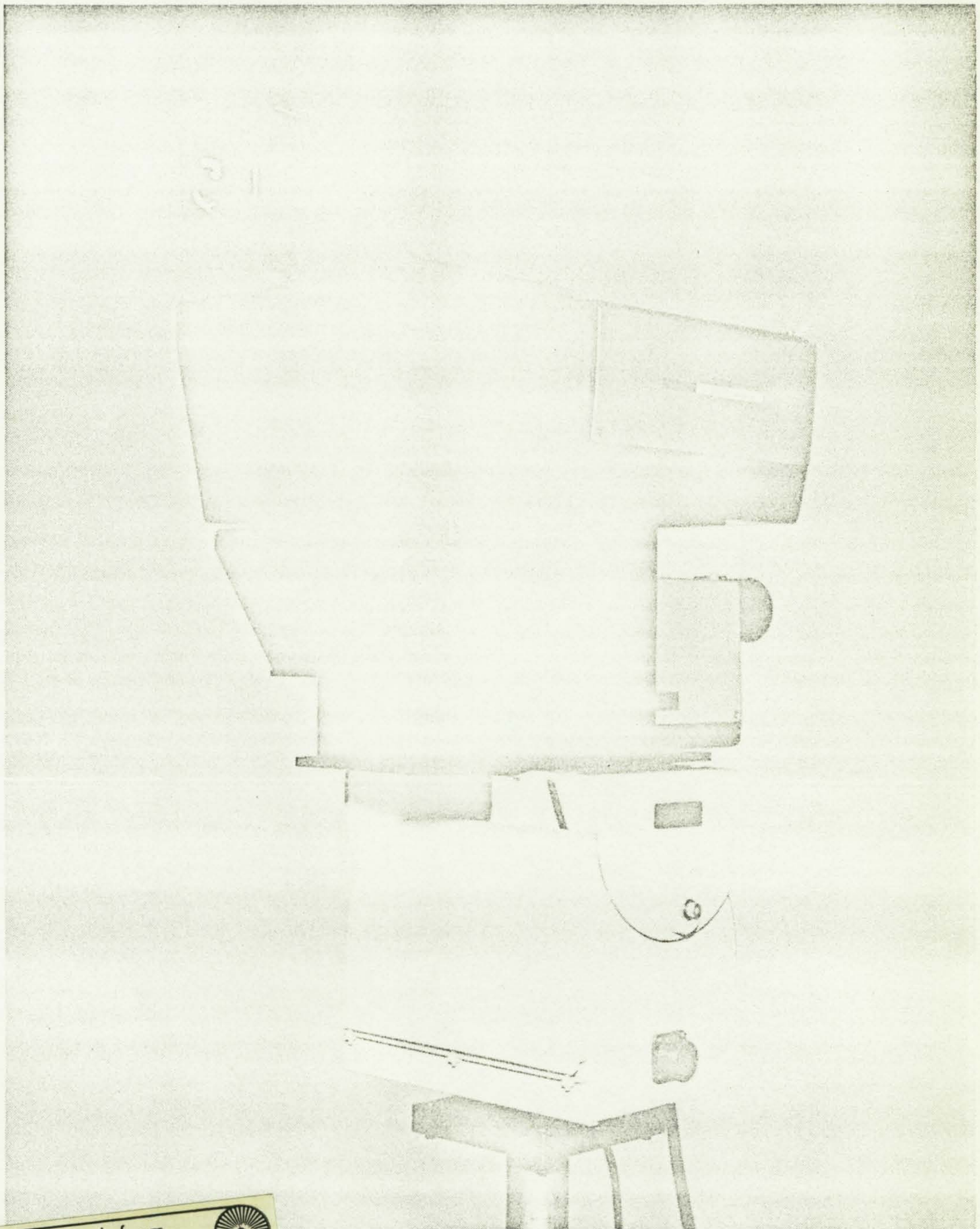

FIGURE 3.3.2-3.
CAMERA SYSTEM -NOTE:
Lens of Wide Field Camera is Visible Behind Beamsplitter.

mirrors. A unique prism system, invented by A. Schwartz at MBA (Figures 3.3.2-4 and 3.3.2-5) rotated the two field halves by 90 degrees (each in opposite directions) in order to obtain registration of the stereoscopic images on symmetric portions of the picture tube. This eliminated differential aberration in the two stereo images that would impair stereoscopic perception. The arrangement also provided for a lateral resolution about one and one-half that of the vertical resolution, leading to optimization of stereoscopic acuity (vertical object contours producing the stereoscopic perception). The video system was a 525 line standard. The horizontal resolution of the cameras was about 400 lines. Illumination was provided by a 650-watt tungsten halogen movie light mounted on the beamsplitter hood (Figures 3.3.2-1 and 3.3.2-3). The cameras are mounted on a Pelco PT-155S pan-and-tilt unit (NASA/AEC property).

3.3.3 Display System

Two monitors and a mirror system similar to that utilized in the camera system were used. The peripheral and the foveal field were made to register concentrically to the observer's field-of-view (Figure 3.3.3-1). The eye position was fixed and an eye hood was used to avoid interference by ambient light to the observer. The last mirror of the symmetric foveal stereo system was a beamsplitter so that the wide field monitor could be seen through it. The mirrors preceding the beamsplitter were rotated in such a way as to make the optical axes of the eyes converge at the surface of the peripheral display tube in order for the two stereoscopic fields to coincide and to minimize registration discrepancies between the foveal and peripheral fields.

The area on the peripheral display corresponding to the stereo-foveal display was blanked out with a black mask. Two negative lenses of 0.5 diopter power were used to bring the vertual image of the stereo display to the same distance to the eye as the peripheral display.

The stereoscopic display subtended an angle of approximately $8^{\circ} \times 12^{\circ}$ and the peripheral display $26^{\circ} \times 40^{\circ}$ (vertical x horizontal). The

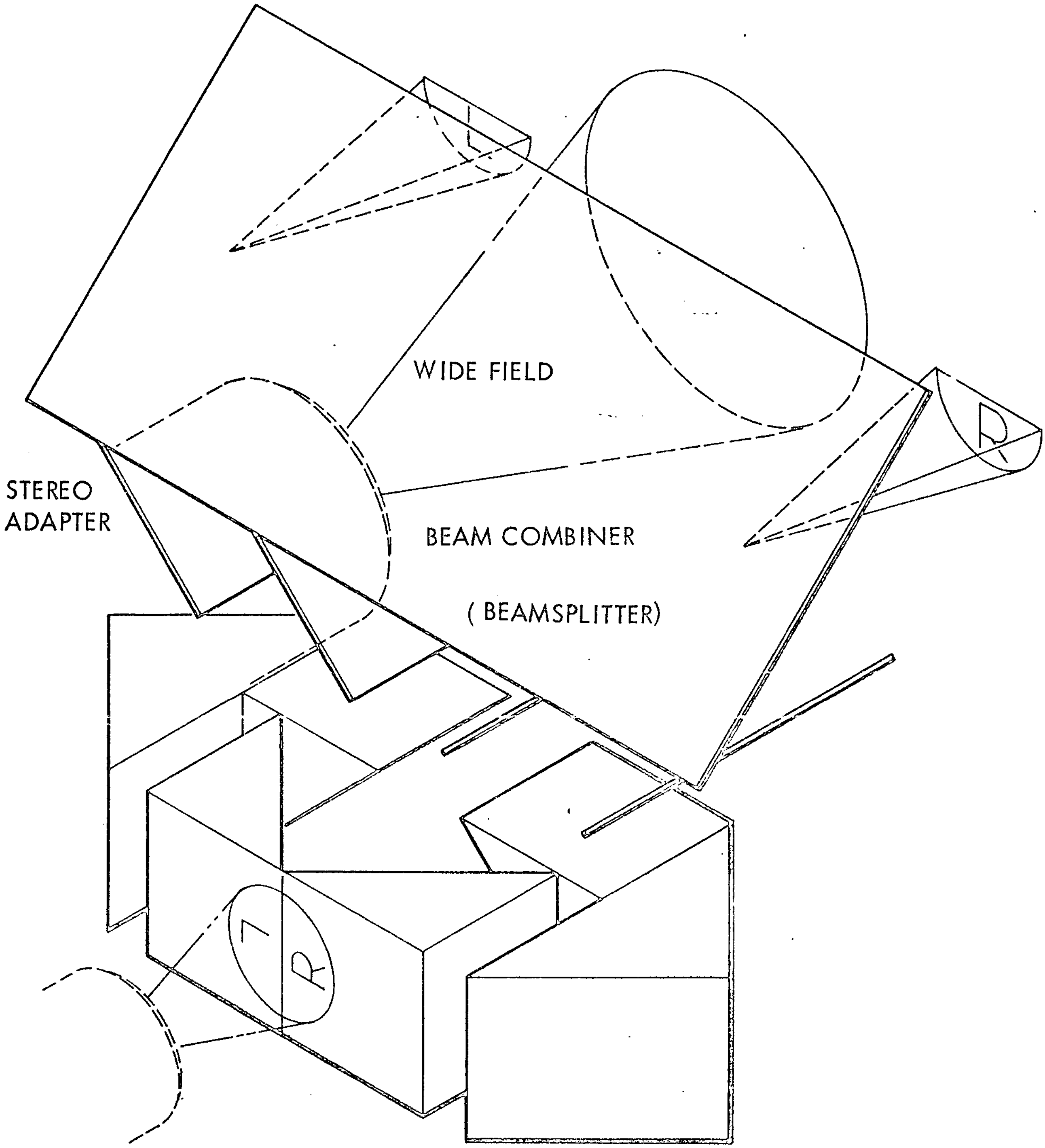

FIGURE 3.3.2-4.
PRISM AND MIRROR SYSTEM FOR STEREO FOVEAL CAMERAS -SCHEMATIC

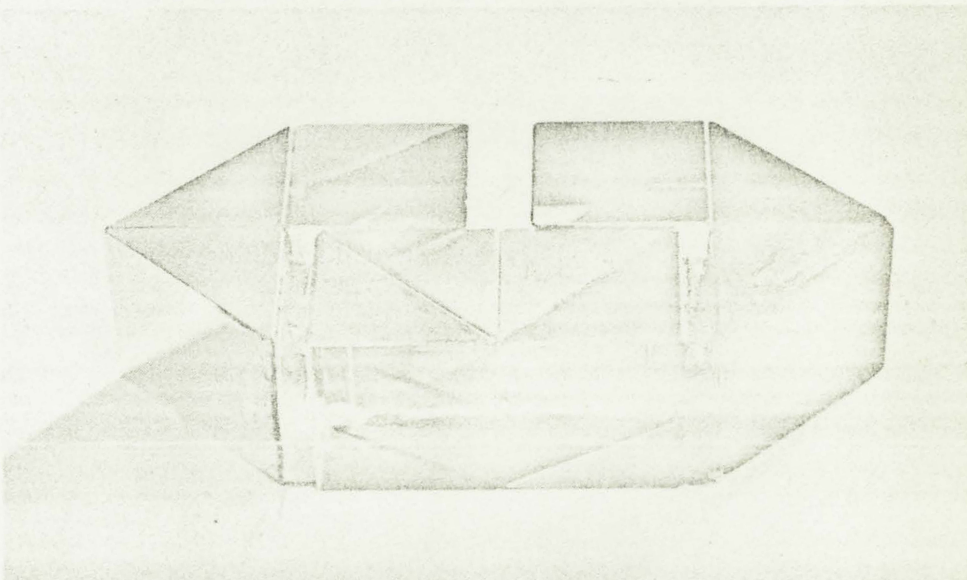

FIGURE 3.3.2-5.
PRISM SYSTEM

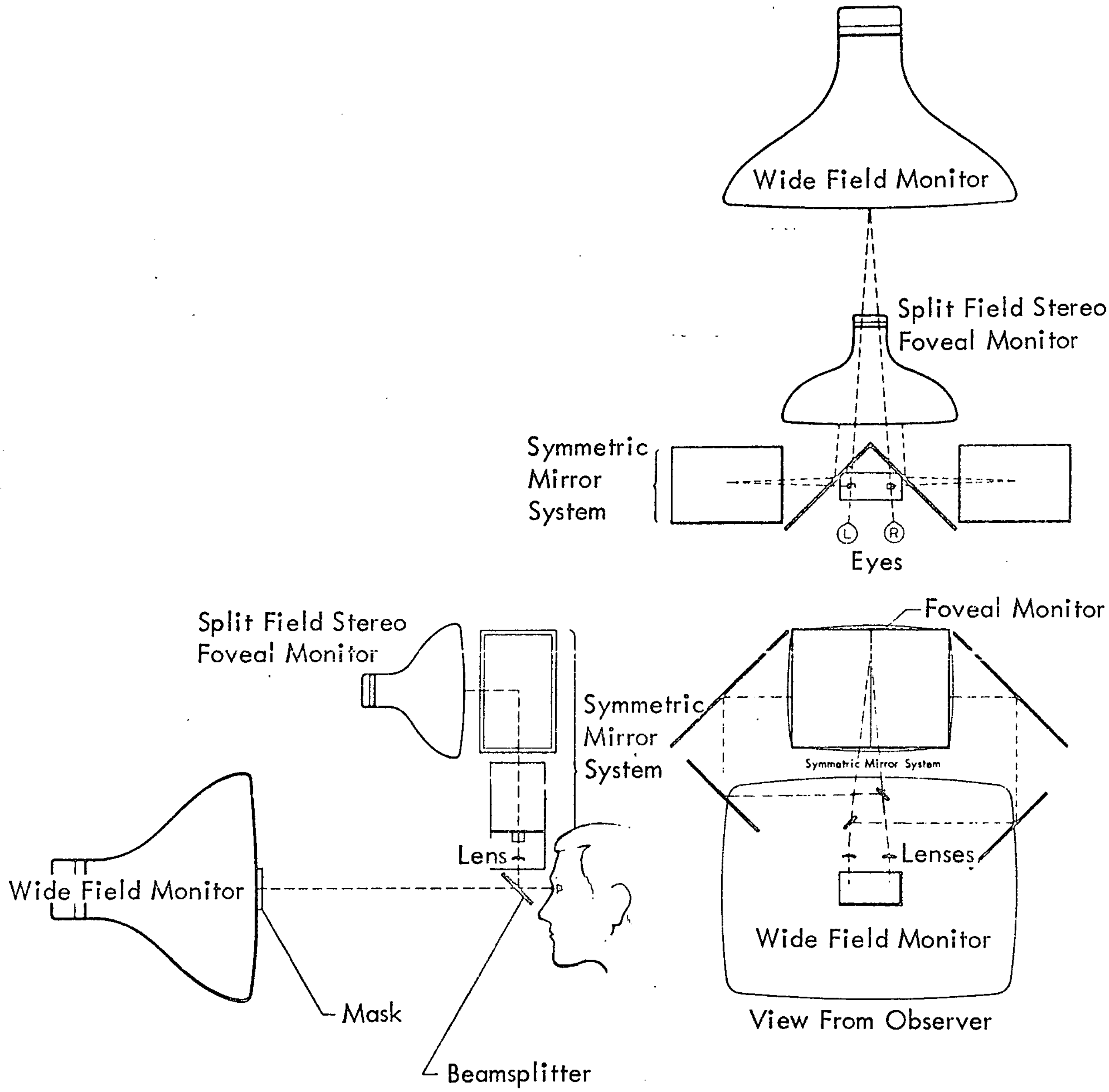

FIGURE 3.3.3-1.
DISPLAY SYSTEM SCHEMATIC

2 x 3 aspect ratio of the stereoscopic display was determined by the splitting of the 4 x 3 standard field. The configuration of the display enclosure is shown in Figures 3.3.3-2 and 3.3.3-3. The remote controls for camera pan and tilt and stereoscopic convergence were mounted on the left side of the display enclosure.

3.4 Results

The specific configuration of the simulation system as well as the field size ratio are a result of the constraints imposed by use of GFE equipment such as camera size, stereoscopic adaptor, camera lens characteristics and monitor size.

The proposed objectives were achieved as follows:

- Feasibility and performance of the system was proven. Good and immediate stereoscopic perception was experienced by a number of approximately 30 untrained observers performing a depth matching test with a precision ranging from approximately 3mm (.118 in.) to 1mm (.039 in.) in depth using the NAT arm (Figure 3.4-1) on their first try.

- There is no need for stereoscopy on the peripheral field display. Stereoscopic perception is operative only at the center of the visual field. The imperfect field border registration due to the stereo-monocular mismatch did not prove to be disturbing. This mismatch is due to the fact that the two stereoscopic fields would coincide with the peripheral field only in a plane passing through the convergence point.
  In the far field, where the axes of the stereoscopic half fields are parallel, the system reverts to a simple foveal-peripheral setup, with complete foveal-peripheral field match.

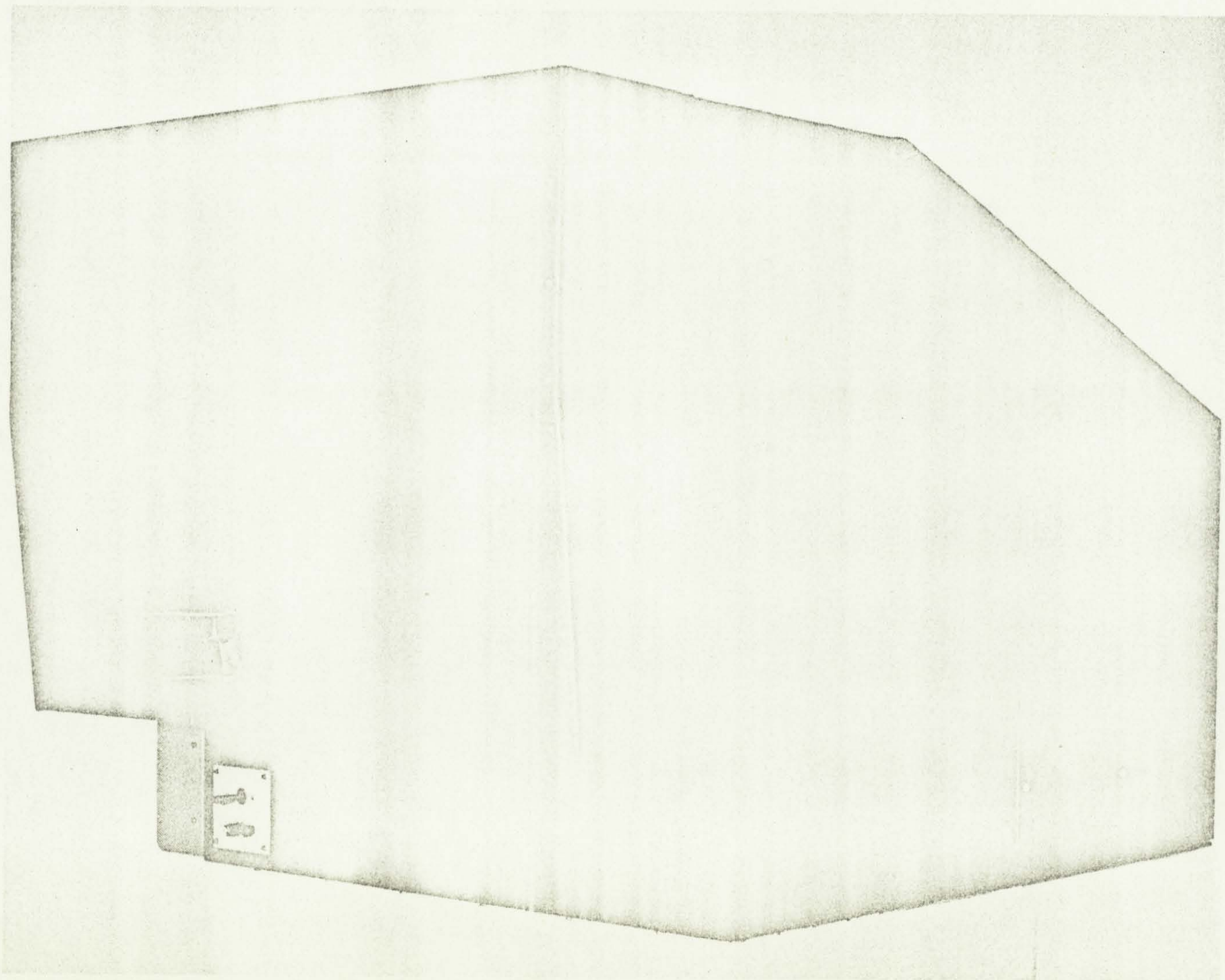

FIGURE 3.3.3-2.
DISPLAY SYSTEM OVERVIEW. Eye Hood, Joystick For Camera Pan And Tilt Control At Left. Covers Of Access Holes To Monitor Controls On The Right Side Of Enclosure.

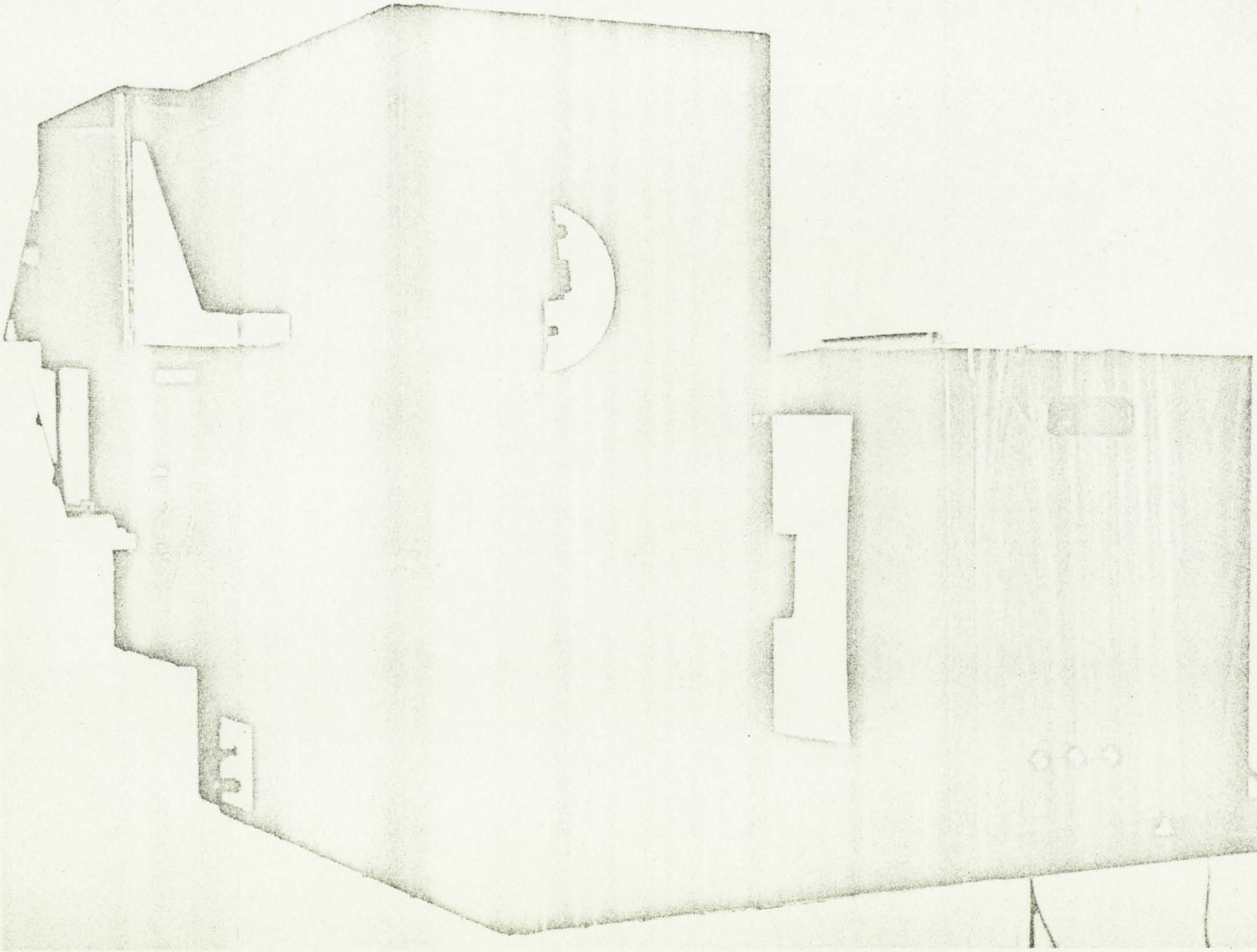

FIGURE 3.3.3-3.
DISPLAY SYSTEM WITH COVERS REMOVED TO SHOW MONITORS AND MIRROR SYSTEM. Foveal Field Blanking Mask Is Visible On The Peripheral Monitor.

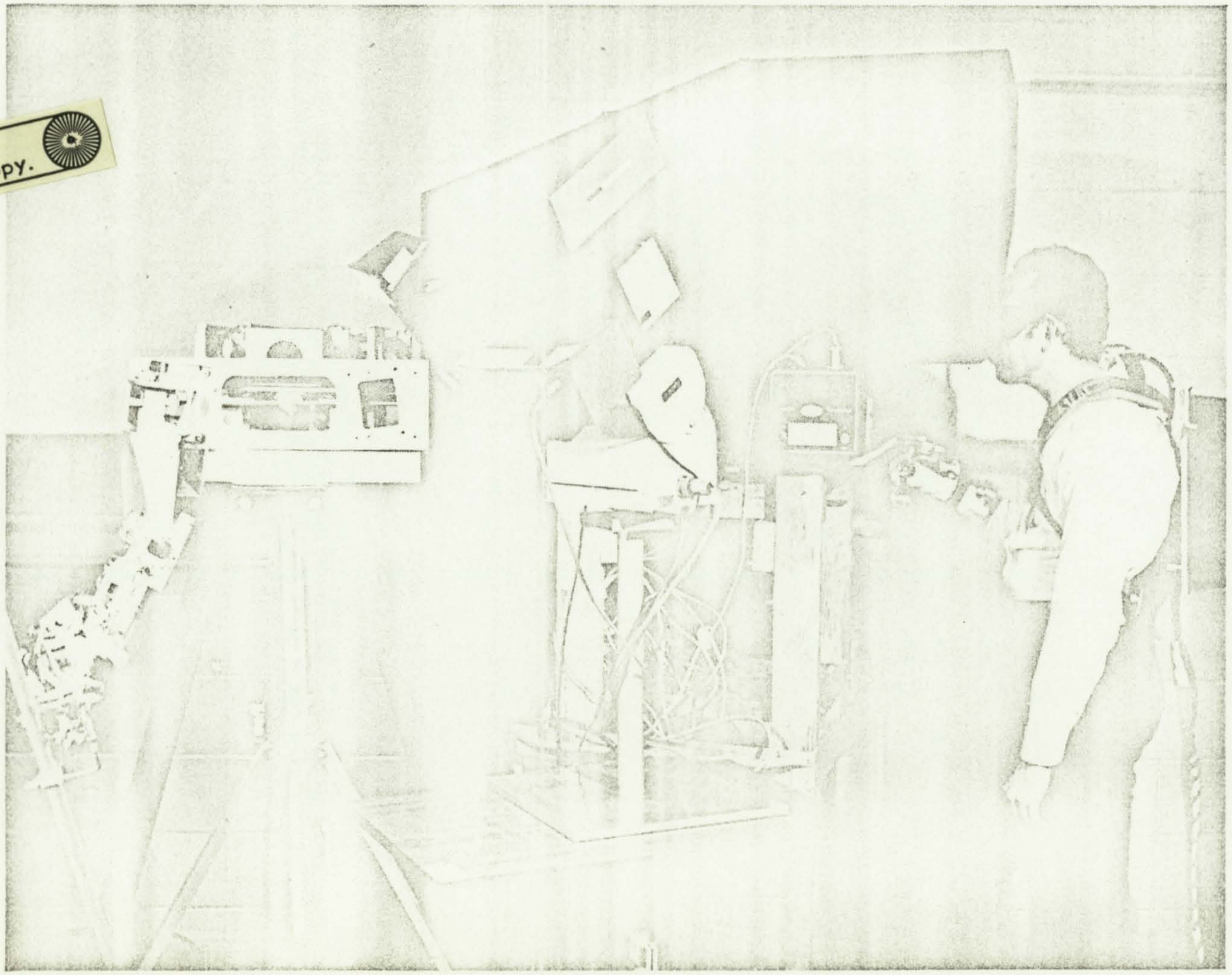

FIGURE 3.4-1.
BOLT & NUT ASSEMBLY USING LABORATORY STEREO-FOVEAL TV AND NAVAL ANTHROPOMORPHIC TELEOPERATOR SYSTEMS.

- The 90 degree counter-rotation concept was proven to function as predicted.
- Two convergent achromatic lenses of 60 cm (24.5 in.) focal length were used to project the apparent distance of the display to infinity. They were discarded in this particular setup because of their tendency to degrade the image. This conclusion may not be valid for other setups.

Figure 3.4-2 presents stereoscopic pairs of views of the display as seen by a camera from the observer's viewpoint. These are presented only as documentation. No attempt should be made to use a stereo viewer with them since the printing process does not allow their reproduction with enough resolution to perceive the stereo image. Interested readers are urged to contact Donald F. Adamski to arrange a demonstration of the system at MBA.

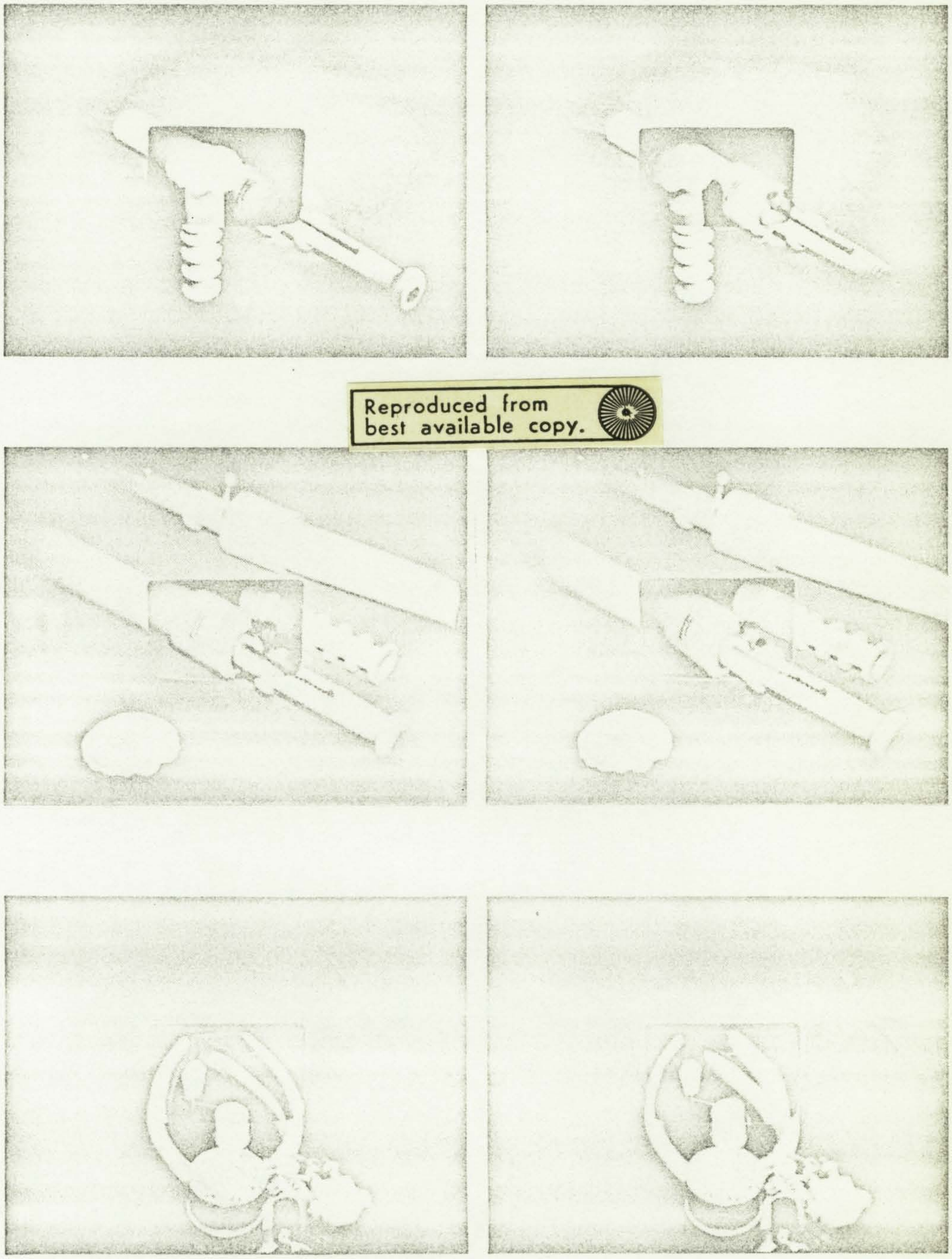

FIGURE 3.4-2.
STEREOSCOPIC PAIRS OBTAINED WITH THE LABORATORY
STEREO-FOVEAL TV SYSTEM

4.0 DEVELOPMENT OF A TRAJECTORY FOLLOWING CONTROL SYSTEM

4.1 Introduction

Trajectory Following Control (TFC) is a new technique for controlling a slow moving, high inertia remote manipulator. The basic concept was conceived by MBA. Refinement of the concept and development of the TFC simulation program described herein was accomplished by Perceptronics, Inc., under a subcontract to MBA. The operational TFC system was implemented and demonstrated at the MBA plant using a mini-computer and the Naval Anthropomorphic Teleoperator (NAT) (a hybred electro hydraulic manipulator developed by MBA).

The following discussion describes the development and operation of the prototype system. This system is a first attempt to implement the approach. Results of operational runs during the simulation have proven both its feasibility with a minimal computer hardware system and its capabilities of aiding a human operator in the control of the Shuttle and Space Station manipulator system.

In addition to providing assistance to the operator, the TFC could be used in conjunction with a Supérvisory Control System and real time end point control system. The TFC provides a means for entering motion trajectory data into a computer memory in a compressed form. These trajectories can be called out at any time later in order to move the manipulator. The TFC can be further developed and enhanced by combined operation with an environmental computer map. Under this scheme, the operator can generate an "approximate" trajectory of motion while letting the computer check the trajectory for possible collisions and adjust its path for any required corrections.

4.2 Objectives

Development of the TFC simulation program was undertaken to demonstrate the feasibility and advantage of using a "computer-assisted"

model control system for the Shuttle and Space Station manipulator system. The main object is to aid the operator in the control of a remote manipulator in a situation where a critical difference exists between his comfortable response speed and that of a manipulator. Such a case exists aboard the Shuttle and Space Station where manipulator motion rates are limited to values much slower than required for compatibility with human response speeds. This is due to the large size of the manipulator (18 m $\approx$ 60 ft) and the small allowable size of its geometrically similar master (15 cm $\approx$ 0.5 ft) with the resulting 120:1 manipulator tip velocity amplification

When controlling such a system, the operation must either wait for long time periods for the response of the manipulator or he must generate extremely slow varying inputs. The condition is similar to that control task under long transmission delay and is in contrast to the normal control scheme, where the manipulator is able to dynamically follow the inputs of the operator at a reasonable response time.

The TFC approach offers a solution to the control problem by providing a system which resembles a (non-real time) master slave control.

The concept involves a miniature or mini-master (geometrically similar to the large slave manipulator) moved along a trajectory by an operator. A scaled down model of the environment (for example, the shuttle, the shuttle cargo bay, a space station module and the space station) is used as an aid in moving the mini-controller (Figure 4.2-1). The scale of the mini-controller and environmental model are identical. The environmental model is slightly larger in its scaled dimension than the physical object it represents to provide an inviolatable clearance envelope around the object the actual manipulator is handling (i.e., desire that the manipulator never comes within 30.5 cm (1 ft) of any portion of the space station - the dimension of the station module is therefore 4.57 m dia + 0.3 m (15 ft dia + 1 ft) clearance or 5.2 m (17 ft) dia - a 1:120 model would be 4.3 cm (1.7 in) diameter).

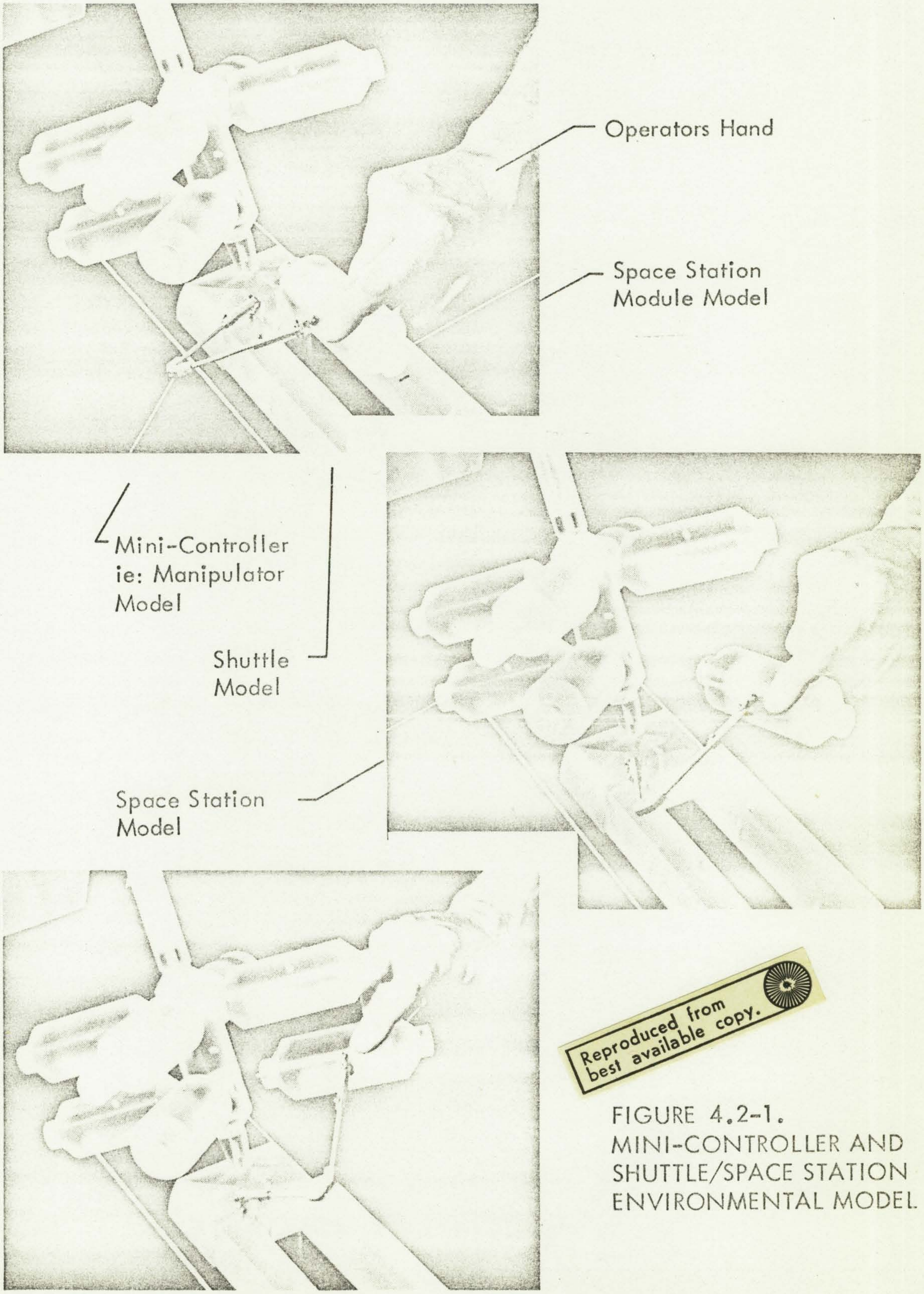

FIGURE 4.2-1.
MINI-CONTROLLER AND
SHUTTLE/SPACE STATION
ENVIRONMENTAL MODEL

The trajectory of movement is interpreted by the computer as a time function defining the motion of each manipulator joint. The computer utilizes an adaptive program which smooths the input data and transforms it to a control signal which is compatible with the dynamics of the manipulator. The generated control signal maintains the original synchronization between the joints while moving the manipulator at a slow steady motion. A schematic of the system is shown in Figure 4.2-2.

The distinct advantage of the man-computer control approach of the TFC is:

- Input trajectories can be generated by the operator at his own pace and motion rates.
- The operator is relieved of the burden of matching his input signals to the dynamics of the manipulator.
- Perturbation and noise in the trajectory of movement which are caused by the operator are smoothed and corrected by the computer.
- The operator can generate "end point" control commands such as movement along flat surfaces or contours by simple positioning of the end point of the small model.
- The operator is relieved of any active control while the computer moves the manipulator and is free to perform secondary tasks.

4.3 Description

4.3.1 Program Functional Description

The functional basis for the TFC system is a real time adaptive computer program which generates a control function to the manipulator. The program functions are described in Figure 4.3.1-1. These functions are:

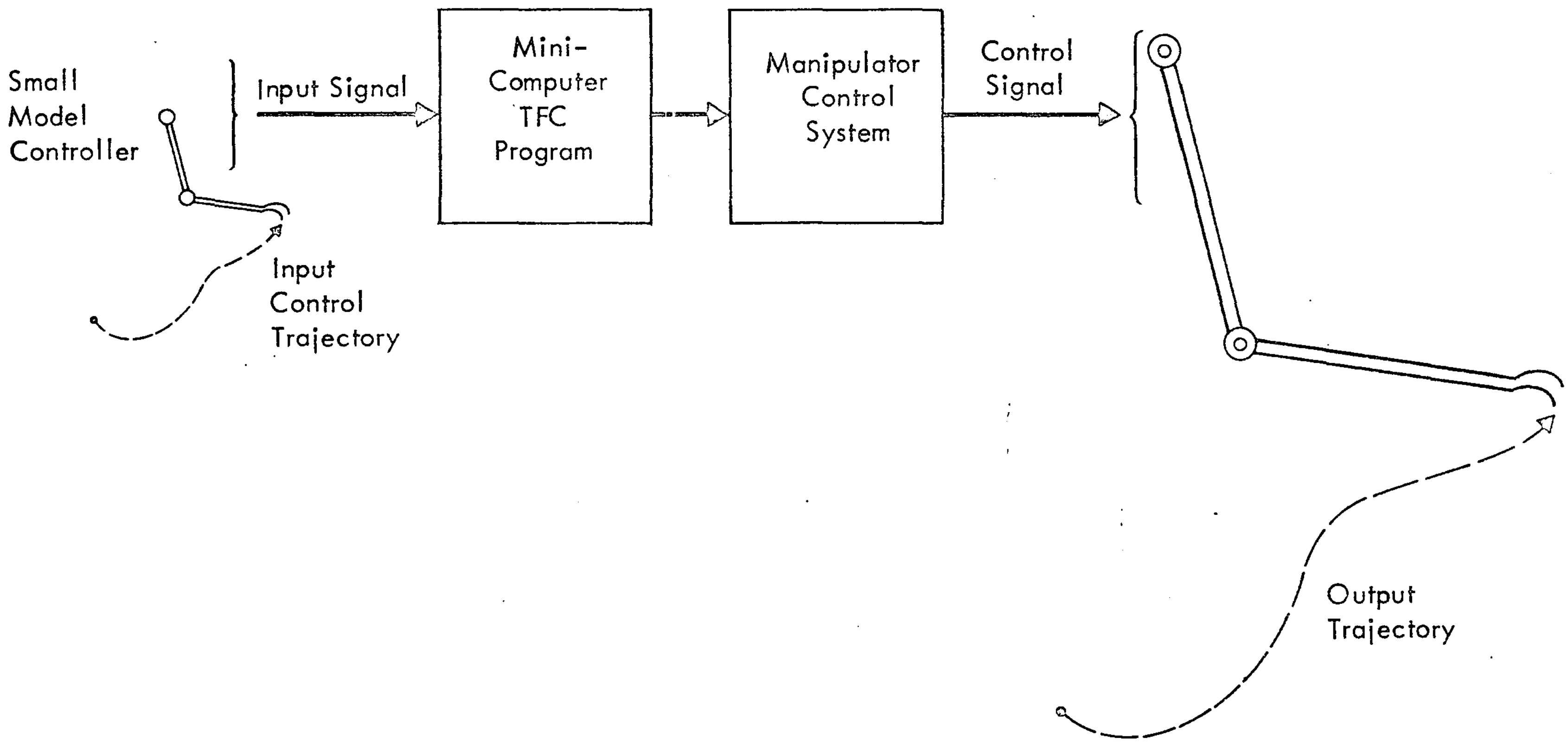

FIGURE 4.2-2.
TRAJECTORY FOLLOWING CONTROL SYSTEM CONCEPT

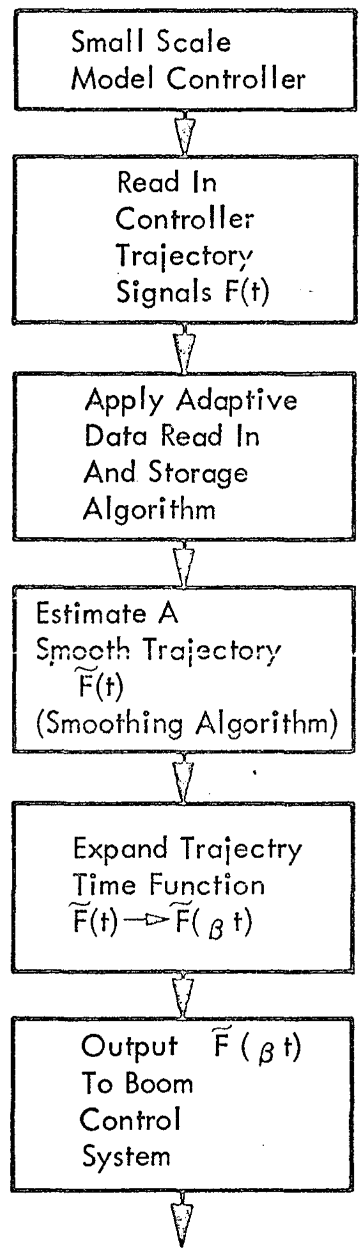

FIGURE 4.3.1-1
TRAJECTORY FOLLOWING CONTROL PROGRAM

- The program reads in analog signals which define the trajectory of movement of the "small model controller" consisting of a function F(t).
- The trajectory data points are read in and stored by an algorithm which adjusts the sampling rate to the rate of change of (the fastest component) F(t).
- The input data points are processed by an exponential smoothing algorithm to eliminate small signal perturbation and estimate a smooth trajectory, $\tilde{F}(t)$.
- The program adapts the trajectory $\tilde{F}(t)$ to the dynamics of the manipulator boom by expanding the time functions. A second order polynomical is used to expand the trajectory data point. The expanded time function is $\tilde{F}(\beta t)$ where β is the time expansion variable.

The program incorporates adaptive features which enhance the overall capabilities of the TFC. These features are:

- The available computer memory is conserved by adjustment of the number of digital words which are used to store a trajectory in its frequency bandwidth. This provides for storage capability of very slow moving trajectories over very long time spans (over one minute).
- Trajectory signals which are produced by small perturbation of the controller around a stationary point or by noise are recognized and discarded.
- The trajectory time expansion is adjusted according to the rate of motion of the controller. This capability is important in cases where the operator slows down the motion of the controller in order to obtain increased accuracy. The program will then reproduce the trajectory input by the operator but with decreased variation in speed of the manipulator.

4.3.2 Simulation Program Flow Chart

Figure 4.3.2-1 illustrates the major components of the TFC program for the simulation hardware. Starting at the top of the flow chart, the program operates as follows:

- Four digitized input signals from the A/D converter are read in. Each of the input signals are digitized at a rate of 100 samples per second.
- The rate of change of each of the input signals δ_i is calculated, and is checked whether it exceeds a preset threshold level. If the change exceeds δ_o, it is considered significant to indicate the existance of a motion.
- Sequential trajectory data samples are stored in the core (i.e.: every point, every second, third, fourth, etc. point, depending on the highest level of δ_i and discard the rest).
- If $\delta_i < \delta_o$ all incoming data points are discarded.
- The program then checks whether all control signal points have been outputted to the manipulator, if they were outputted the program checks whether all stored trajectory data points have been executed.
- If the stored data points have not been executed the program calls in the smoothing and interpretation subprograms to generate a smooth expanded control signal. The signal is fed as a sequence of digital words to the D/A converter at a rate of 100 samples per second.
- The program then waits for the next sampling period. At the onset of the sampling period the program repeats a subsequent operational cycle.

The memory requirements to store trajectory data vary linearly with the rate of the controller and the length of time of the trajectory. For a

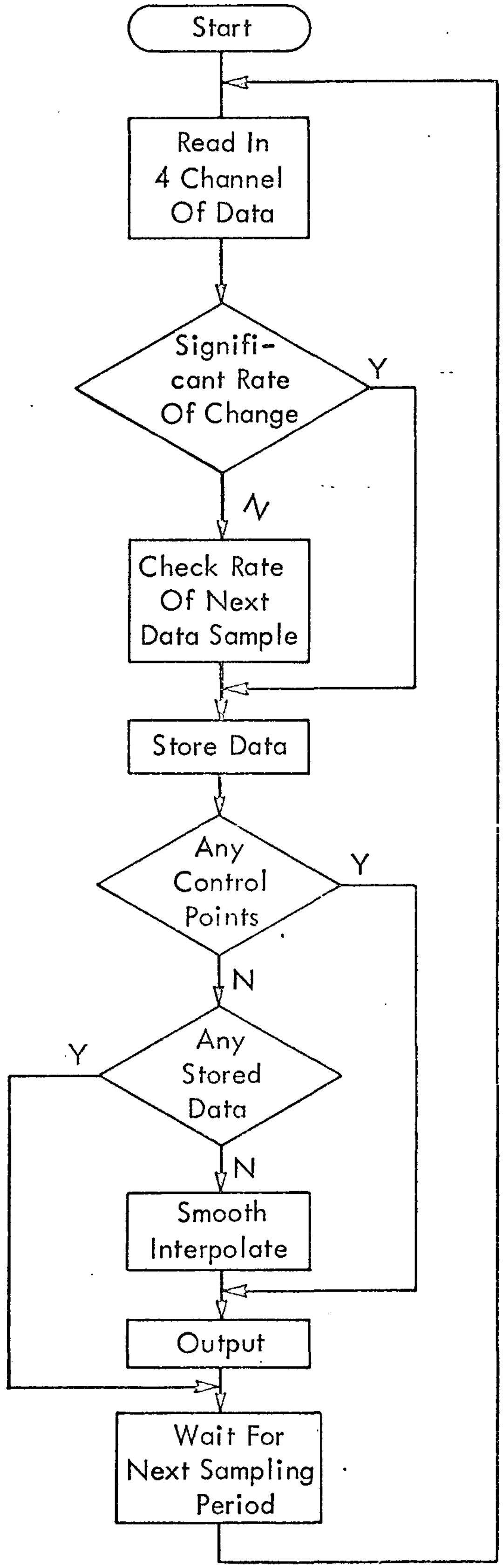

FIGURE 4.3.2-1.
TRAJECTORY FOLLOWING CONTROL
PROGRAM FLOW CHART

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typical joint velocity of 40 degrees/second 33 words will be required per each second of motion. In the simulation with the 4 degrees of freedom manipulator and a controller that was moved with a velocity of 40 degrees/second over 5 seconds 660 words were required for trajectory storage.

4.3.3 Simulation Setup

The implemented Trajectory Following Control system is shown in Figure 4.3.3-1. The system consists of three major components: the "small model" or mini-controller, the computer, and the manipulator and its associated position control system.

The small model controller is shown in Figure 4.3.3-2. The controller is 4:1 scaled down exact replica of the NAT manipulator. The mini-controller has four degrees of freedom which include the basic joint motions required for defining a trajectory in a 3-D space. These joints are:

- Shoulder Az
- Shoulder El
- Elbow flexure
- Wrist flexure

All of the joints of the controller are counter-balanced (Figure 4.3.3-2a) so that its position remains stationary when released. All joints incorporate precision roller bearings and adjustible dampers.

The NAT manipulator is a 9 degree of freedom anthropomorphic remote manipulator developed by MBA under a joint Navy/NASA/AEC contract. Its design use is ordnance disposal. It is currently the latest state-of-the-art in adverse environment precision manipulator systems. It is ordinarily controlled by an anthropomorphic exoskeleton master. The nine joints include:

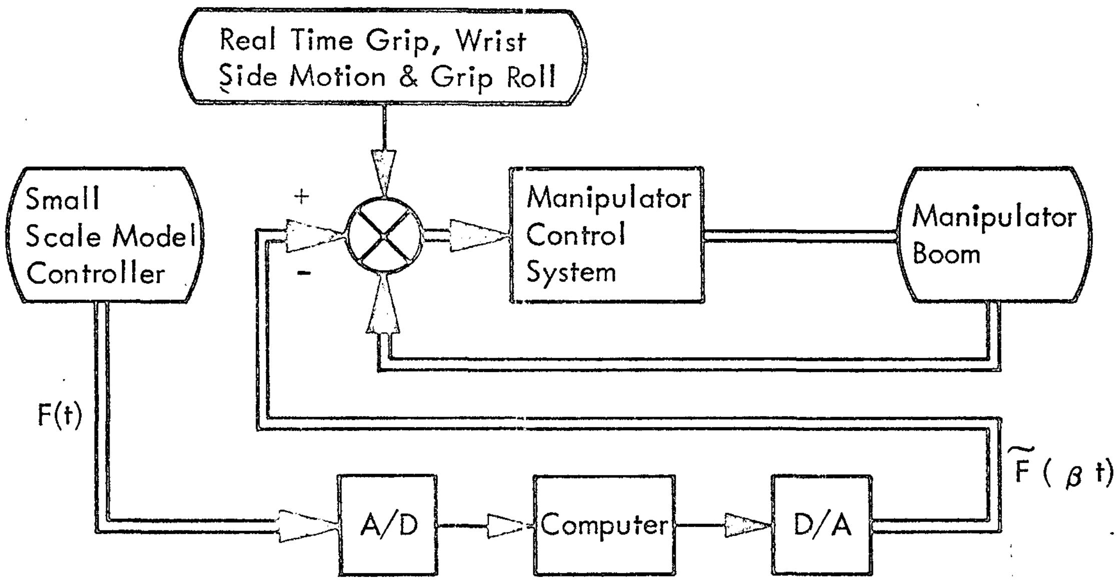
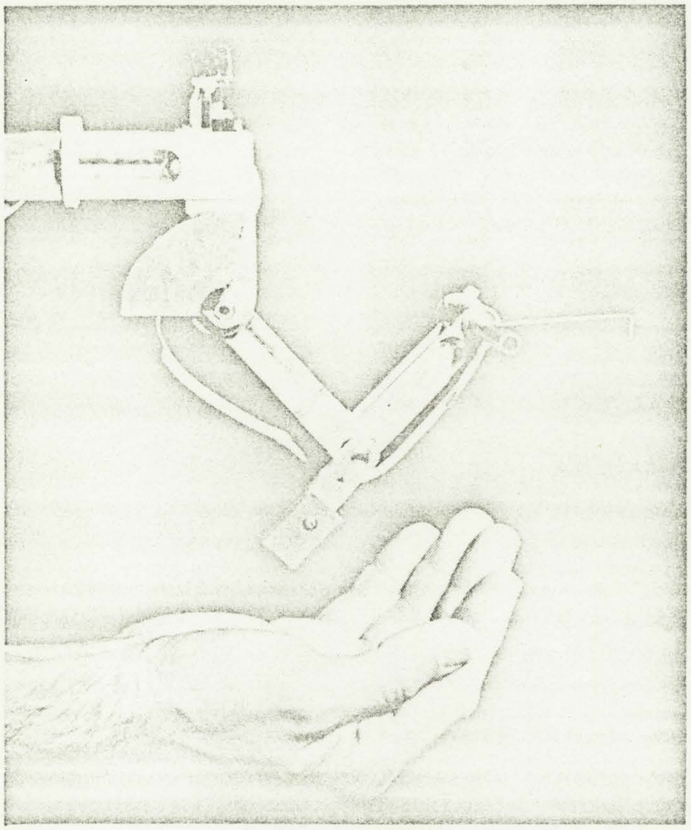
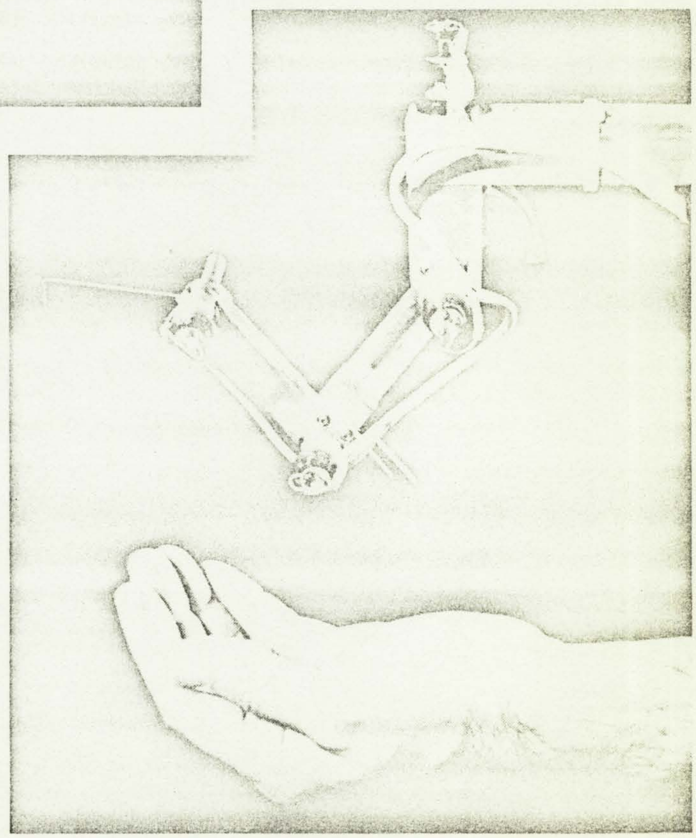


FIGURE 4.3.3-1.
TRAJECTORY FOLLOWING CONTROL SYSTEM SCHEMATIC



(a) Counter-Balance Detail



(b) Potentiometer Detail

FIGURE 4.3.3-2.
NAT MIN-CONTROLLER

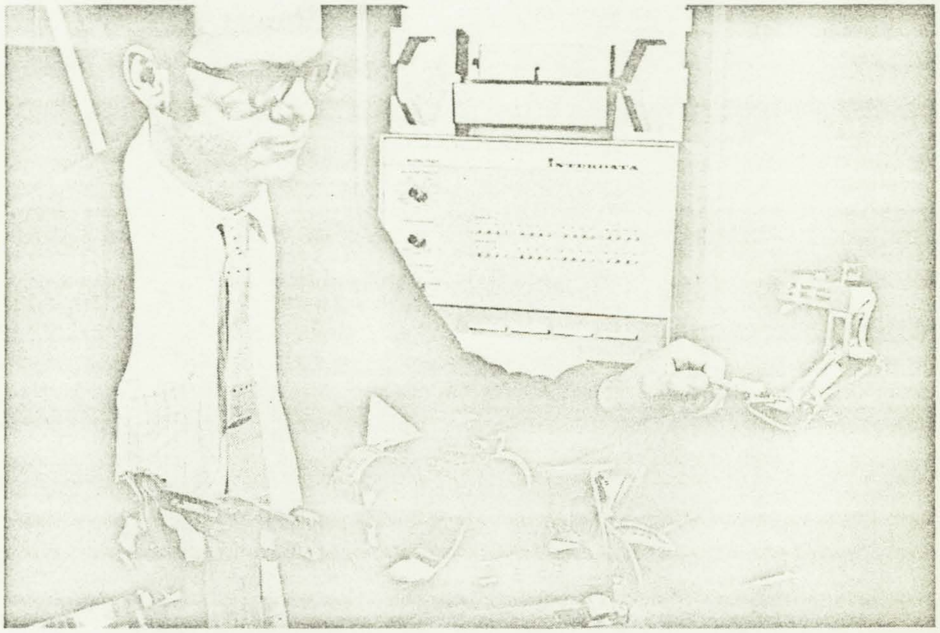
- Shoulder Az
- Shoulder El
- Upper arm roll
- Elbow (one step force feedback)
- Lower arm roll
- Wrist flexure
- Wrist side flexure
- Grip roll
- Grip closure (proportional-linear force feedback)

For the simulation the joints defined in the above paragraph were controlled by the mini-master, the upper and lower arm rolls and elbow force feedback were locked out and wrist side flexure, grip roll and grip closure were operated hands-on-real-time through the wrist assembly of the exoskeleton master which was detached from the full exoskeleton and bolted to the control table (Figure 4. 3. 3-3). Since the NAT system incorporates proportional force feedback in the grip, the use of the wrist assembly of the NAT full scale exoskeleton allowed the operator to use force feedback control when objects are picked up while he let the computer translate the rest of the manipulator to positions specified by the model controller. Figure 4. 3. 3-4 shows the system components as interfaced together.

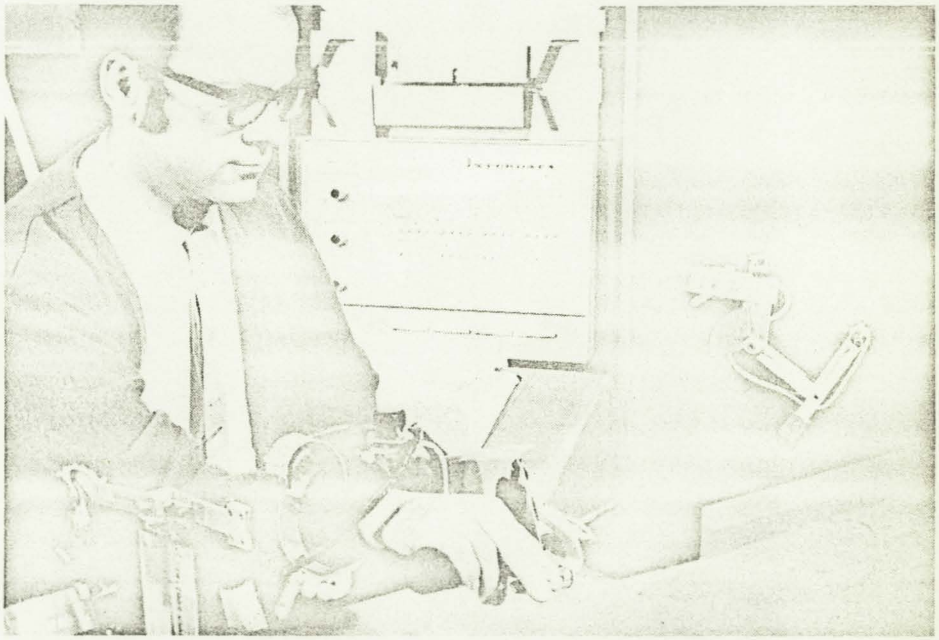
As the system was configured for the simulation the computer was part of the control loop at all times. Trajectory processing began each time the operator repositions the controller. The computer used was an Interdata Model-4 mini-computer with 8K words of memory and associated analog interface equipment.

4.4 Results

The simulation TFC was tested in a set of demonstration runs. The tests involved both computer program performance and operational tests. The results are:



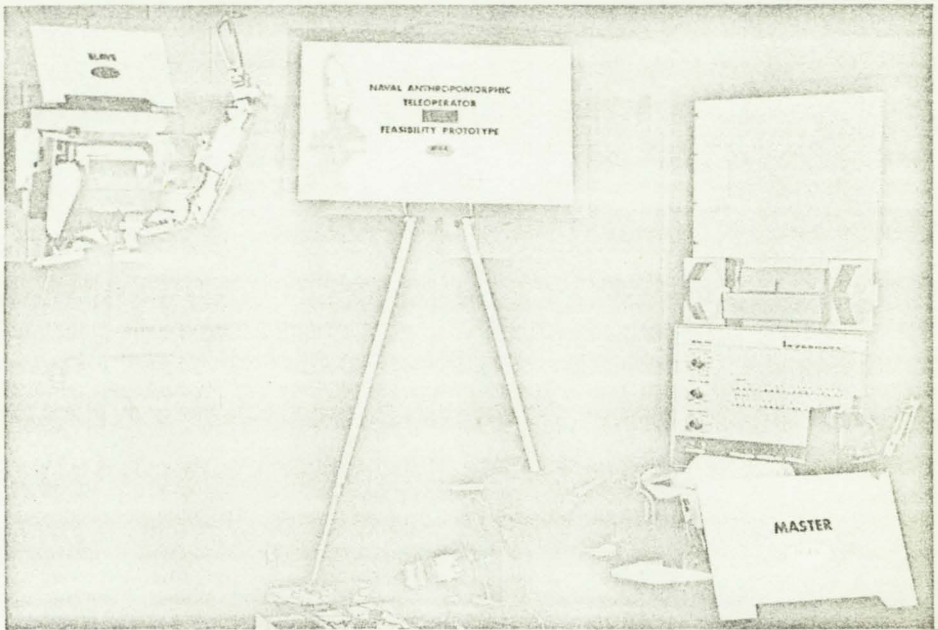
a) Mini-Controller. NAT Joints Controlled Are - Shoulder Az & El, Elbow and Wrist Flexure.



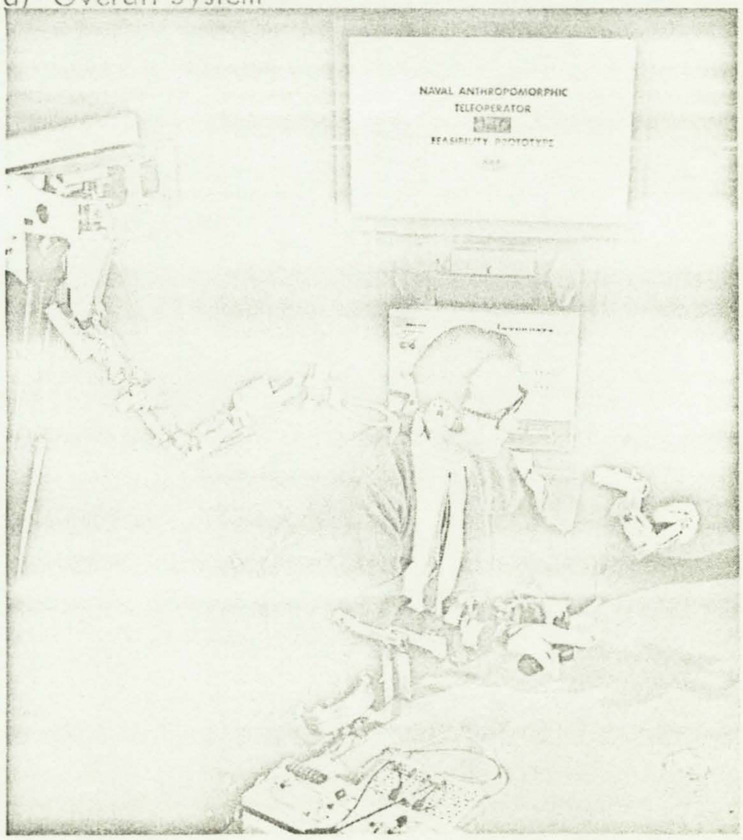
b) Exoskeleton Wrist Controller. NAT Joints Controlled Are - Wrist Side Flexure, Grip Roll And Grip Closure.

FIGURE 4.3.3-3.
SIMULATION CONTROLLER

MBA
0112-10037



a) Overall System



b) System In Use and Under Adaptive Computer Control

FIGURE 4.3.3-4.
TOTAL SIMULATION SETUP

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- Computer control produced a smooth and steady motion in the manipulator regardless of the time scaling (up to 1/30) and jerkiness of motion of the mini-controller.
- Motion trajectories of the controller were accurately reproduced by (under computer control) the manipulator. The highest possible accuracy of the system is 0.2%.
- Untrained operators had no difficulty in moving the manipulator along a specified trajectory.
- Variation of motion rates in the trajectories of the controller were transformed to trajectories with smaller variations and provided close to uniform velocity. Figure 4.4-1 illustrates the rate transformation as obtained from observations of system performance. As input and output trajectories are shown: angular velocity is marked.

The development of the TFC simulation has contributed to the general knowledge which is associated with computer controlled manipulations by the development of specific techniques for trajectory data sampling and storage.

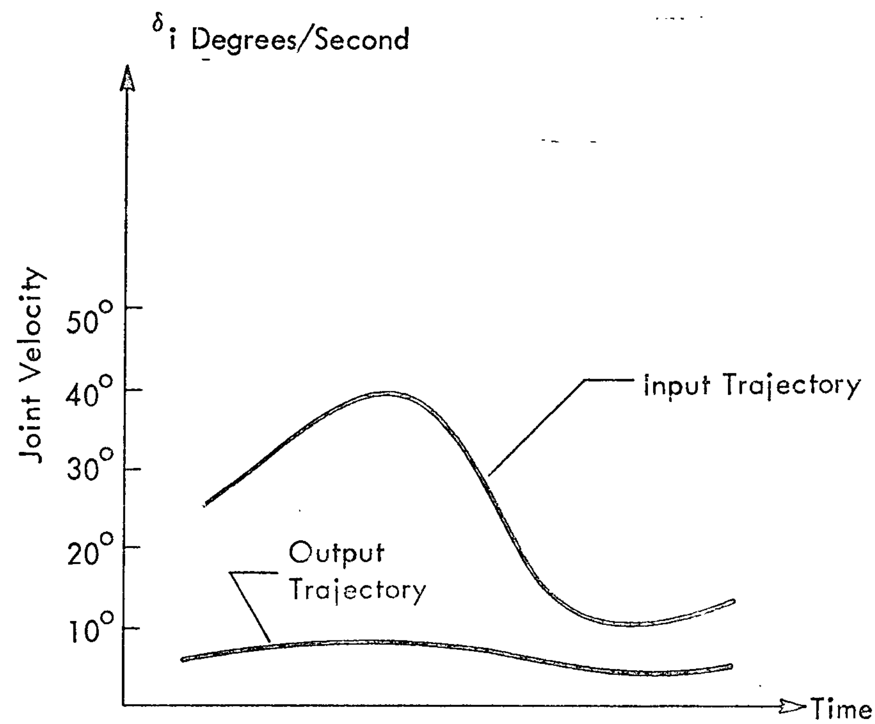

FIGURE 4.4-1.
PROGRAM INPUT AND OUTPUT TRAJECTORIES

5.0 ACTIVE MANIPULATOR DAMPING

5.1 Introduction

NASA/MSC has constrained the material of the manipulator booms to aluminum. The internal or structural damping of aluminum is very low and vibrations induced by motion are slow to damp out by natural means. If motion could be sensed and the signal fed back to develop a force on the boom, damping could be artificially induced in the system. This simulation was performed to demonstrate the feasibility of this concept.

5.2 Simulation Objectives

- Demonstrate the feasibility of electronically induced damping in a simple analog system.
- Evaluate the improvement in damping based on discontinuous starting-stopping motions.
- Record the dynamics of motion.

5.3 Description

A simple spring-mass analog of the space station manipulator boom was assembled to investigate active damping problems (Figures 5.3-1 and 5.3-2). A linear spring was loaded with a mass (the accelerometer) as an analog of the rotational system of the manipulator. The upper end of the spring was driven by a string loop in tension. The string was in turn driven by a drum on a gear reducer d. c. motor. The motor was driven by complimentary power transistors and an operational amplifier. The mass is the object whose position must be controlled. To accomplish control and damping, a force must be imposed that is proportional to the motion of the mass. This motion is sensed by an accelerometer at the mass that responds to the rectilinear acceleration.

The analog system had a resonant frequency that is much higher than the modeled system since sensors for very low frequencies

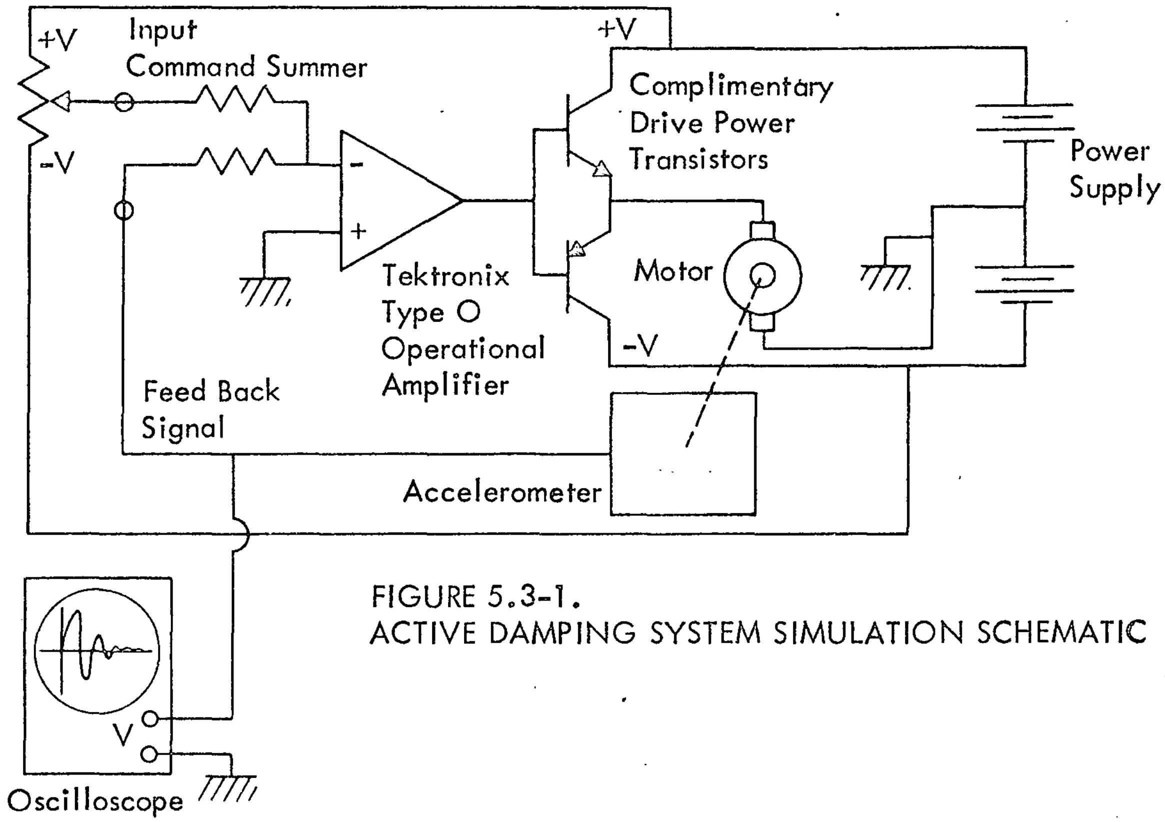

FIGURE 5.3-1.
ACTIVE DAMPING SYSTEM SIMULATION SCHEMATIC

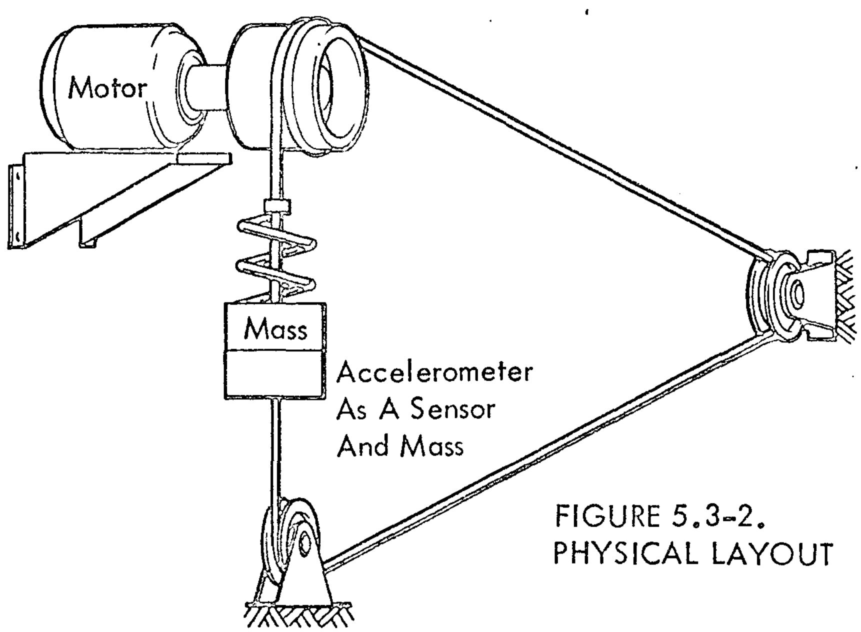

FIGURE 5.3-2.
PHYSICAL LAYOUT

were not readily available. The mass, spring constant, resonant frequency and displacement were scaled for study purposes. The equations of motion show that the period scales as the mass and spring constant scale.

$$m' = am \qquad s = \pm \frac{j}{a}\sqrt{\frac{k}{m}}$$

$$k' = \frac{k}{a} \qquad f = \pm \frac{j}{a2\pi}\sqrt{\frac{k}{m}}$$

$$m\ddot{x} + kx = F \qquad f' = \frac{1}{a} f$$

$$ams^2 x + \frac{kx}{a} = F \qquad T = \frac{1}{f}$$

$$\frac{x(s)}{F(s)} = \frac{\frac{1}{am}}{s^2 + \frac{k}{a^2 m}} \qquad T' = aT$$

Where: m = mass, a = scale factor, k = spring constant, x = displacement, s = Laplace variable, f = frequency, T = period, and F = force. The quantities without primes represent the analog system. The quantities with primes are the modeled system.

5.4 Results

Starting and stopping the mass causes the most easily observed results, both by direct view of the mass motion and by display of the output of the acceleration sensor on an oscilloscope. Figure 5.4-1 is a photograph of the output of the sensor with no feedback damping. Notice that the system has fair natural damping and attenuates to $\frac{1}{e}$ (37%) amplitude in approximately 1.5 seconds (6 cycles) and 5% in 3 seconds (12 cycles). Figure 5.4-2 shows the same system, but with active feedback damping. The amplitude is attenuated to $\frac{1}{e}$ in approximately 0.1 second (.5 cycle) and to 5% in 0.5 seconds (2.0 cycles). The residual motion is partly due to dead band in the actuating motor (for low values of drive voltage no torque is produced) and the limited gain of the amplifier. It is important to notice

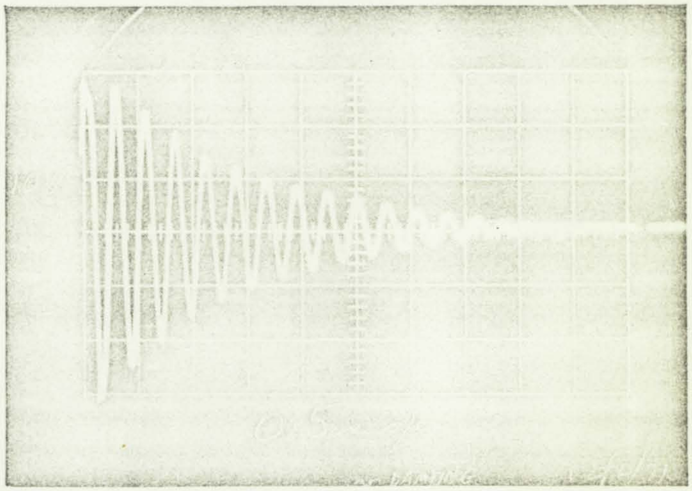

FIGURE 5.4-1.
ACTIVE DAMPING
SIMULATION SYSTEM
UNDAMPED RESPONSE

FIGURE 5.4-2.
ACTIVE DAMPING SIMULATION
SYSTEM DAMPED RESPONSE

that starting and stopping are used as examples, but for adequate control, damping is required for all motions; impulses, ramps and steps of displacement and velocity. A lightly damped system brought immediately to a constant velocity will surge in translation rather than acquire a constant velocity. The control condition is similar to an automobile shock absorber that is required for control at all times; bumps, corners, stopping and accelerating, not just for stopping.

APPENDIX A

Trajectory Following Control System Motion Picture Scene Discription

Lead In: MBA Title Block

Scene 1: Closeup of the mini-master and its range of motion to the right of the scene. The NAT exoskeleton wrist assembly to the left of the scene.

Scene 2: Closeup of the NAT exoskeleton wrist assembly showing real time control of the NAT slave wrist side motion and grip open and close. Grip roll not shown.

Scene 3: NAT slave operating under the TFC program at 1/10 input velocity. The complex, jerky, random input trajectory is being developed by the operator using the mini-master. Illustration of real-time use of wrist flexure and grip closure using exoskeleton wrist assembly.

Scene 4: Simulated mass transfer around obstacles using NAT slave operating under the TFC program at 1/10 input velocity. The objects in the scene are as follows:

Ladder & letter tray	=	Shuttle and its open cargo doors
Glass beaker	=	Space Station Module
Plastic Cup	=	Small Airlock Module
Overturned gray waste-basket	=	Space Station Core Module

Note the clear plastic scale model of the overturned gray waste-basket and the machinist's pointer in front of and directly to the side of the mini-master, respectively. The machinist pointer represents a scale model of the shelf of the stepladder to the left of the scene.

Scene 5: Same as Scene 4 with NAT slave operating under the TFC program at 1/30 the input velocity. The TFC time delay can be easily programmed to any value.